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Survey of Emissions Control and Combustion Equipment Data in Industrial Process Heating

Institute of Gas Technology, Chicago, Ill

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SURVEY OF EMISSIONS CONTROL AND COMBUSTION EQUIPMENT DATA IN INDUSTRIAL PROCESS HEATING

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16. ABSTRACT

The report ~~gives results of investigations of~~ the interaction between present and potential energy conservation measures and emission programs in a number of select industries. Where energy conservation goals conflicted with emission control goals, the problems were assessed. Based on these assessments, research and development programs were recommended to solve each industry's problems. The study was limited both to processes in which heat was obtained through the direct combustion of fossil fuels, and to emissions that are affected by combustion itself. It was concluded that information is available on emission problems and control technology associated with particulate emissions and stack plume opacity, as well as stack gas acidity, carbon monoxide, and unburned hydrocarbons. However, not much is apparently known about the level of NOx emissions from industrial heating processes. There are several areas of concern, all related to the apparent conflict between energy conservation and emission control goals: (1) the ability to meet voluntary energy conservation goals is substantially decreased by the energy consumption of emission control devices required by more stringent future emission standards; (2) application of energy conservation measures will lead to increased air pollutant emissions, particularly for NOx; and (3) the trend away from clean-burning gas.

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SUMMARY AND CONCLUSIONS

The subject of the investigations in this program was the interaction between current and potential energy conservation measures and emission programs in a number of select industries. By interviewing representatives of these industries, information in both areas was obtained. Where the goals of energy conservation are in conflict with emission control goals, as assessment of the problems involved was obtained. Subsequently, this information was evaluated at the process level for each industry investigated and an independent assessment of the problem areas was made. Based on the results of this assessment, R & D programs were recommended for each industry to solve the problems involved. The scope of the program was limited to processes whereby heat was obtained through the direct combustion of fossil fuels (as opposed, for example, to electricity), and it was limited to emissions that are affected by combustion itself.

The persons visited appeared to be well acquainted with both emission problems and control technology associated with particulate emissions and stack plume opacity, as well as stack gas acidity, carbon monoxide, and unburned hydrocarbons. However, there did not appear to be much known about the level of the NO_x emissions from industrial heating processes.

During these visits, several areas of concern were expressed by the persons contacted, all of which related to the apparent conflict between energy conservation goals and emission control goals. First, an almost universal concern was that the ability to meet voluntary energy conservation goals is substantially decreased by the energy consumption of emission control devices required by more stringent future emission standards. A related concern was that application of energy conservation measures would lead to increased air pollutant emissions, particularly where NO_x emissions are concerned. No specific examples involving NO_x emissions were offered because there are no standards against which data might be compared, although several areas where the goals might be in conflict were mentioned; for example, the preheating of combustion air using heat will increase NO_x emissions. However, there is some evidence to indicate that, at least in the case of NO_x emissions, emissions will not increase in situations traditionally thought to result in increases. For example, the use of oxygen enrichment for melting has been shown not to result in increased NO_x emissions, although current information concerning NO_x formation would suggest that it should. Consequently, one general recommendation is that programs be undertaken in each industry (where applicable) to demonstrate the conformity of available energy-conserving process modifications with the goals of reduced air pollutant emission controls. As the data indicate, most of these problems are concerned with NO_x emissions, although there are select instances within each industry involving other emissions. A second recommendation is that programs be undertaken to develop more efficient, lower energy-consuming pollution control devices.

Another area of common concern among the industries investigated is the trend away from clean-burning gas to liquid and solid fuels. This trend will result in increased emissions from combustion, which in turn will require additional control equipment. The additional control equipment, as already noted, will require additional energy, and it is claimed that the use of these fuels results in a loss of process efficiency. Although there is some skepticism as to the latter point, it nevertheless deserves investigation. There are some processes in some of the industries that are capable of using liquid and solid fuels at increased efficiency. Programs should thus be undertaken to clearly demonstrate the efficiency of such processes for both energy conservation and emission control. Where there are real problems involving efficiency of liquid and solid fuels, programs should be undertaken to resolve them, even to the point of developing hardware, the use of which would have widespread impact — for example, the development of a low-NO_x, oil- or coal-fired burner that meets the requirements of both air pollutant control and efficient fuel utilization. Beyond these general recommendations, specific recommendations for each industry are presented in the respective sections of this report. It is clear from the data gathered that there are many processes in industry where energy consumption can be reduced without detrimental environmental impact, and that the demonstration of these processes will result in an increase in their implementation by industry.

INTRODUCTION

The purpose of this study was to identify the significant emission sources within the industrial process-combustion field, to investigate the potential for effective emissions control for industrial process combustion, and to compile information on combustion equipment in use and future trends in process and equipment design. This program investigated the interactions between current and potential energy conservation measures and emission control programs, assessed the potential for R&D work to advance emissions control, and recommended R&D programs to solve the problems involved.

The program was divided into three distinct phases for the purpose of industry selection, data collection, and data analysis.

The first phase of this program (Phase I) was to determine those industries and industrial processes which have a high potential for conserving energy and reducing emissions. Their selection was based on the relative amounts of energy consumed and the relative emissions of pollutants. The selection process included consideration of the potential for simultaneous energy conservation and air pollutant emission controls.

The second phase of this program (Phase II) consisted of an intensive series of visits to industrial plants, corporate headquarters, trade associations, and builders of process heating equipment. The purposes of these visits were to validate and fill the voids in the information collected in Phase I and to assess a number of elements relating to existing and future trends in process technology and equipment design affecting energy consumption and air pollutant emissions.

The information obtained from the trade associations, equipment builders, and industrial plants was correlated and analyzed in Phase III to provide an assessment of process and equipment design and operating factors that are major influences on both fuel efficiency and air pollutant emission rates. This data analysis resulted in estimates of the potential for improvement in fuel-use efficiency and reduction of emissions for existing equipment designs and for new processes and equipment designs that may be instituted in the future. Upon completion of the data analysis, recommendations for specific programs aimed at reducing energy consumption and air pollution emissions were made, including the identification of potential sponsors for these programs.

PHASE I. INDUSTRY SELECTION

In a program of this type, it is generally not feasible to consider all industries. Consequently, a system was developed for selecting pertinent industries. The system related energy consumption, pollution emissions, and the potential for reducing both for each industry, and then determined the relative merits of studying each industry in terms of achieving the program objectives. Toward this end, the following system of restraints and weighting factors had been developed for selecting the industries to be studied in this program.

Restraints

The first step in the development of this system was to define the restraints as determined by the problems to be solved. The following restraints were selected:

1. Total energy use in process heating. This program is primarily concerned with those industries that consume large amounts of energy because it is in these industries that the most significant results of implementation of energy conservation technology will be realized. Some industries, however, consume large amounts of fossil fuels for feedstock and steam generation — ostensibly, the paper industry, the chemical industry, the petroleum refining industry, and the food-processing industry. In the areas of feedstock and steam generation, little can be done to alter the energy utilization patterns. Consequently, only those industries that consume large amounts of energy for process heat are being considered in this program.

2. Combustion-related uses of energy. A further refinement of the first restraint is to limit the investigation to combustion-related aspects of energy consumption. In so doing, industries which consume large amounts of purchased electricity for process heating will be eliminated from consideration. Electricity consumption is not within the scope of this program, although in-plant generation may be considered if the relative load is large enough.

3. Relative number of processes within an industry. In some industries, energy is consumed by a large number of relatively small-scale processes, which, when added together, show a very large total energy consumption figure for the industry as a whole. Typical of such an industry is the industrial chemical industry. The total amount of energy consumed for process heating in the chemical industry in 1972 was about 2800 trillion Btu. However, most of this energy was consumed in the manufacture of thousands of chemicals which incorporate myriads of individual processes with varying energy requirements. To study an industry such as this would give minimal return toward the project objectives in that reductions in energy consumption of a process in this industry would have a minimal effect on the national energy picture. On the other hand, in an industry with a limited number of processes, such as the cement industry, in which more than 90% of the

581 trillion Btu of energy consumed in 1972 was consumed in kilns, even a small (5% to 10%) increase in fuel utilization efficiency of the kiln would have a significant, widespread impact on the entire industry as well as the national energy picture.

4. Known and/or estimated total emissions. Two of the stated purposes of this program are to identify the significant sources of emissions within the industrial process combustion field and to determine the potential for effective emissions control for industrial process combustion. Therefore, the emissions of an industry must be a restraint in the industry-selection process. Emissions from industrial process combustion can be broken down into three categories:

   a. Emissions directly related to combustion — typically NO_x, SO_x, CO, and particulates.

   b. Emissions indirectly related and therefore somewhat controllable by combustion techniques — typically such emissions as particulates from a glass melter or cement kiln where the combustion gases "pick up" the dust of the raw material and carry it out the stack.

   c. Emissions independent of the combustion process — typically emissions from chemical reactors or electrolytic processes.

5. Types of emissions — NO_x, SO_x, CO, and particulates. These are the emissions of primary concern in this program as they are the emissions most closely related to the combustion process. Secondary emissions of concern are fluorides, chlorides, and other halides, although these are only indirectly related to the combustion process.

6. Potential for energy conservation. Energy conservation is one of the primary purposes of this program. Consequently, only those industries which have a high potential for reducing energy consumption should be considered. The paper and paperboard industries, although consumers of large amounts of energy (more than 1300 trillion Btu in 1972), will be eliminated from consideration because 95% of this energy is consumed as boiler fuel, an application which already has a direct fuel utilization efficiency greater than 80%. The potential for increasing the efficiency of direct utilization of fuel is low.

7. Potential for reducing emissions. Reducing combustion-related air pollutant emissions is the other primary objective of this program. Consequently, as in the case of energy consumption, those industries with a low potential for reducing emissions will not be considered in this program.

Upon applying the restraints and a weighting system (Appendix A), the following industries were selected for study in this program:

- Iron and steel (all energy-using processes)
- Cement (primarily kiln operation)
- Glass (melting, forehearth operation, annealing)

- Aluminum (primary, reheating, secondary production)
- Petroleum refining.

These industries ranked highest in terms of the evaluation characteristics used in this program. That is, all of these industries use large amounts of process heat directly from the combustion of fossil fuels; all of these industries are relatively large emitters of combustion-related air pollutants; and all of these industries have a high potential for reducing energy consumption and air pollutant emissions. Note that these industries have been selected based on the combination of all of the above factors. Consequently, there are industries, such as the paper and paperboard manufacturing industry, that consume twice as much energy as the cement industry and 4 times as much as the glass industry, but, because 95% of that energy is consumed in boilers to generate steam (a process efficiency in excess of 80%), the potential for reducing energy consumed directly by the boilers is very low. Thus, this industry received a low priority rating and is not being considered in this program. Information related to the industries considered for this study is shown in Table 1.

Table 1. PROFILE AND WEIGHTING FACTORS FOR INDUSTRIES CONSIDERED FOR STUDY IN THIS PROGRAM

Industry	Total Energy Consumed, 10^{12} Btu/yr	% Consumed for Process Heat	Weighting Factors			
			Base Energy Number	Emission Index No.	Potential Energy Consumed	Potential Emissions Recorded
Iron and Steel	3100	80	22	10	10	10
Industrial Chemicals	3764	55	14	4	5	5
Soda-Ash	161	75	20	4	6	6
Petroleum Refining	2861	60	12	5	3	3
Paper and Paperboard	1307	5	14	7	2	5
Cement	581	90	24	8	10	7
Food	911	5	11	5	2	3
Glass	250	90	22	7	8	7
Plastics and Synthetics	755	10	11	2	2	2
Aluminum	352	80	15	7	5	5

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PHASE II. DATA COLLECTION

Iron and Steel Industry — Processes and Equipment — Current State-of-the-Art

The major operations in an integrated steel plant are the coke oven, blast furnace, basic steelmaking, rolling mill, and finishing.

Coke Ovens

Coke is the product of destructive distillation of some types of bituminous coal, commonly referred to as metallurgical coal. It is produced in by-product coke ovens, sometimes called slot ovens, because of their shape. Each oven is a narrow, rectangular retort closed at the top except for charging ports, with gas off-take ports in the sides and bottom. Each end of the oven is fitted with a tightly sealed removable door. One end is the "pusher end" from which a ram is inserted to push out the coke; the other end is called the "coking end" from which the hot coke is pushed into a quenching car. Adjacent retorts are separated from each other by heating flues and are called underfired ovens because the air and fuel ports are located at the bottom of the heating flues. A large number of the retorts and associated flues are stacked together, and the entire series is called a battery.

High-, medium-, and low-volatile coals are crushed, ground, and blended to obtain the desired coking characteristics. About 65% to 80% of the charge is high-volatile coal containing 30% to 40% volatile matter. After charging the retort, the coal is converted into coke in approximately 16 to 18 hours in older ovens and in about 12 hours in modern, taller ovens equipped with improved combustion and control systems.

By-products of the coking operation include coke-oven gas, tar, ammonium sulphate, and light oil products (BTX). About 60% of the sulfur content of the coal is carried over into the coke. The balance goes to the coke-oven gas as hydrogen sulfide. A representative material balance for a coke-oven plant is shown in Table 2.

The fuels used for heating the coke-ovens are selected on the basis of cost, availability, and combustion characteristics. Top to bottom temperature gradients must be minimized. Coke-oven gas and a natural gas-air mixture provide the desired high flame temperature. Blast-furnace gas has a much lower heating value and a lower flame temperature, but a high concentration of inerts that act as diluents to retard combustion and lengthen the flame.

Table 2. COKE-PLANT MATERIAL BALANC⁻

	Quantity	Pounds/Ton of Dry Coal
Coke	78.5%	1574.0
Coke-Oven Gas	10,600 cu ft (540 Btu)	312.3
Tar	7.55 gal	74.8
Ammonium Sulfate	21.0 lb	21.0
Light Oil Derivatives	2.85 gal	20.9
Total		2000.0

The primary fuel for underfiring coke ovens has been coke-oven gas. About one-third of the coke-oven gas produced is used for this purpose. Blast-furnace gas and natural gas together account for 15% to 20% of the total input for underfiring coke-ovens. (Total fuel input for underfiring has been about 3.0 million Btu per ton of coke produced.)

The major technological trends affecting coke-oven energy requirements are —

- Higher and wider ovens using high conductivity refractories. Coking rates and productivity have increased; however, increases anticipated in efficiency have been offset by higher coking temperatures and greater heat losses. Thermal efficiencies of coke ovens are reported in the range of 60% to 70%.
- Predrying of Coal Charge. Predrying of coke increases coke-oven productivity and reduces heat losses resulting in a saving of about 100,000 Btu per ton of coke. Emissions during charging of predried coal are also reduced.
- Use of Formcoke. Formcoke is a calcined agglomerate of bituminous coals (noncaking). Pollution in formcoke processes is also reduced.
- Improved Blast Furnace Operations. The quantity of coke required per ton of pig iron produced is reduced by using a higher top pressure, hotter blast air temperature, oxygen enrichment of blast air, and increased use of fuel injection.
- Direct Reduction of Agglomerated Iron Ore. Direct reduction and electric furnace melting produce steel with no pig-iron requirement and prereduction of part of the blast furnace burden will reduce the coke requirements and increase blast furnace output.

Blast Furnace Plant

The blast furnace and its associated stoves for preheating blast air, the sinter plant, and storage, sizing and handling facilities for raw materials are the major components of the blast furnace area in an integrated steel plant.

Sinter Plant

Some of the iron ore and flue dusts are available in particle sizes less than 1/4 inch and cannot be charged directly to the blast furnace. These products are mixed with flux and coke breeze and loaded onto a traveling grate-sintering machine. An auxiliary fuel such as natural gas, coke-oven gas, or oil is used to initiate combustion on the surface of the mixture and is referred to as ignition fuel. Combustion is continued over the length of travel by forcing air through the mixture on the grates. The mixture is heated to a fusion temperature, which causes agglomeration of the iron-bearing particles. The sinter discharged is cooled, crushed, and screened prior to transfer to the blast furnace charging oven.

The major source of energy used in the production of sinter is the carbon content of coke breeze and flue dust. The amount of ignition fuel required is about 0.12 million Btu per ton of sinter. The total fuel requirement, including coke breeze, is about 2.0 million Btu per ton of sinter.

Blast Stoves

Blast stoves are checker-brick-lined chambers used to supply heated air to the blast furnace. The stoves are regenerative heat exchangers, during part of the cycle being heated by combustion of blast-furnace top gas and during another part of the cycle heating the blast air. Three or four stoves are required for each blast furnace. In operation, a stove heats air until the air preheat temperature drops to a preset value. The stove is then isolated from the hot blast main and reheated by combustion of blast-furnace gas to the temperature required to heat blast air. Regenerative air preheating results in a cyclic variation in blast-air temperature, and the stoves may be used as staged temperature preheaters in various combinations with the objective of reducing the cyclic variations in blast temperature.

The thermal efficiency of the blast stove is quite high — about 72% — as would be expected from a regenerative heat exchanger. However, efficiency has decreased from about 87% in 1960 because of a continuous increase in blast temperature. Average blast temperature in 1969 was in the 1500° to

1600°F range and in 1960 was below 1300°F. Some installations are now approaching a 2000°F blast temperature.

The major reasons for increasing blast-air temperature are to reduce coke consumption in the blast furnace and to increase the output of pig iron. Auxiliary fuel injection in the blast furnace also requires higher blast-air temperature to maintain temperature in the melting zone. Other factors also affect coke rate and production. These will be discussed in the blast-furnace section of this report.

About 25% of the blast-furnace top gas is used for stove heating. In 1969, this amounted to 165 trillion Btu. Increases in blast-air temperature and a reduction in blast furnace gas heating value have required the use of coke-oven gas and natural gas for higher heat release in blast stove heating.

Current technology trends in blast stove design and operation include —

- Improved designs for burners and combustion chambers
- Improved hot valve designs
- Better refractories and checker-brick design
- Automatic stove charging equipment
- Improved modes of stove operation.

Blast Furnace

The blast furnace is a cylindrical, tapered, refractory-lined, vertical furnace. It is charged with the basic iron-making raw materials, iron ore, pellets, sinter, coke, and limestone, and discharges hot metal or pig iron and a slag that contains the mineral gangue and other impurities. It is a counterflow process in that the iron-making materials are charged at the top through a double-bell seal and travel down through the furnace reacting with an ascending stream of reducing gases, primarily carbon monoxide and hydrogen. The reducing gases are produced by blowing preheated air through ports, called tuyeres, into the bottom of the furnace, where reaction with the incandescent coke takes place. Auxiliary fuels such as fuel oil, natural gas, tar, or powdered coal are frequently injected at the tuyeres to increase iron output and decrease the coke rate. With auxiliary fuel injection, higher blast-air temperature or oxygen enrichment is usually required to maintain the iron melting temperature. Exceptionally good results have been achieved on a pilot-plant basis by injection of reformed natural gas at the tuyeres. Theoretical calculations have shown that even better results could have been obtained by injection of hot reformed gas above the tuyeres in the gaseous reduction zone. Although these programs have been curtailed by reduced availability of natural gas, the results indicate that blast-furnace injection may become a potential application for use of low-Btu gas produced by gasification of coal, assuming a favorable economic justification. A suitable reducing gas can also be produced by partial oxidation of residual oil, but the present cost and availability of low-sulfur oil make this approach uneconomical.

Pollutants From Iron-Making

The coke-oven plant has been identified as one of the major sources of air and water pollution from integrated steel plants. Some of the sources of emissions are —

- Coal handling, processing, and storage
- Charging the coal into the ovens
- Leakage during coking, particularly from the doors
- Discharge of incandescent coke
- Water quenching of coke
- Contaminated water discharged.

A variety of methods has been incorporated in recent coke-oven plant designs to effectively control emission of pollutants.

Sinter plants are inefficient as users of energy and are major contributors to steel mill particulate and gaseous emissions. Emission control is technically difficult and expensive. Some steel plants have phased-out sinter lines, and pelletized iron ore has now assumed a dominant position as a major blast-furnace charge. Pelletizing plants are located near the iron ore sources and the emissions from the pelletizing process do not contribute to the steel mill emission control problems.

The major pollutants from sinter plants are particulates, sulfur oxides, and carbon monoxide. Leakage from the seals between the exhaust ducts and the sintering furnace structure accounts for most of the emissions.

Disposal of in-plant fines and flue dust as process feedstocks will be required by means other than landfill. Both pelletizing and hot-briquetting will probably be used.

The emission of pollutants from blast-furnace stoves consists of dust carried over from the blast furnace. With properly designed combustion systems and air/gas ratio controls, carbon monoxide should not be considered a significant emission. Particulate emission from blast-furnace stoves is not treated separately in the literature, but is considered part of blast-furnace particulate emissions.

Steelmaking

In steelmaking, iron from the blast furnace, commonly called hot metal, and scrap are charged along with fluxes to melting process equipment. Impurities such as carbon, manganese, silicon, and phosphorous are oxidized to or below specified levels during the melting process. These oxidation reactions are exothermic and contribute part of the total process energy requirement. The fluxes and some of the oxidized impurities form a slag layer, and the rest of the oxidized components leave as gases. The major types of melting process equipment are the open-hearth, the basic oxygen furnace (BOF), and the electric furnace.

Open-Hearth Steelmaking

The open-hearth furnace is a large reverberatory vessel heated from the top by burners located at each end of a long, narrow chamber. A long, luminous flame is produced so that a high percentage of heat transfer to the bath is by radiation. The heating process is regenerative in that refractory checker-brick are located downstream of each firing port so that combustion air is being preheated at one end, while exhaust gases are reheating the checker-brick at the other end. After a timed interval the flow is reversed. Scrap metal, fluxing agents, iron ore, and hot metal are charged through doors located above the bath level along the length of the furnace. Open-hearth furnace capacities range from 100 to about 600 tons per heat.

The high productivity of competitive steelmaking processes has brought about major improvements in open-hearth furnace productivity. Some of these improvements are oxygen-enrichment of combustion air, roof-mounted oxygen lances, roof-mounted oxygen-fuel lances to accelerate scrap melting, and higher combustion-air preheat temperature. However, the use of oxygen lancing has resulted in increased dust loading of the waste gases and this has required installation of more costly air pollution control equipment.

Fuels used in open-hearth furnaces include residual oil, natural gas, coke-oven gas, tar, and pitch. Part of the thermal requirement is provided by exothermic oxidation of impurities contained in the hot metal portion of the charge. Fuel required per ton of steel produced is in the 1.5 to 4 million Btu range, depending on the hot metal-scrap ratio and the amount of oxygen lancing used.

Basic Oxygen Furnace (BOF) Steelmaking

In the BOF process, oxygen is blown downward through a water-cooled lance into a bath containing scrap and hot metal. Heat produced by oxidation of carbon, silicon, manganese, and phosphorous is sufficient to bring the metal to pouring temperature and auxiliary fuel is not required. The furnace is an open top, tiltable, refractory-lined vessel shaped somewhat like the old-fashioned glass milk bottle. Furnace capacities range up to 300 tons and the time required per cycle is very short – from 45 to 60 minutes.

The BOF has displaced the open-hearth as the major steel production process, but is much less flexible because of the inherent limitation of 25% to 30% scrap in the charge. The amount of BOF capacity in an integrated steel plant is, therefore, closely associated with hot metal availability. Additional flexibility in scrap use can be obtained by preheating the scrap with an oxygen-fuel burner. In many steel plants, an open-hearth shop is modernized and equipped with appropriate pollution control equipment so that it can be used in conjunction with BOF shops to provide the required flexibility to accommodate variations in hot metal-scrap ratio. A combination of BOF shops and electric furnace shops provides the maximum in flexibility and may represent the makeup of future steelmaking facilities.

Excluding fuel use for scrap preheating, other uses are for refractory dryout and to keep the BOF vessel from cooling between heats. Their uses amount to about 200,000 Btu per ton of steel produced.

Decarburization of the iron charged to the BOF produces about 400,000 Btu of carbon monoxide per ton of steel. The off-gases also contain large amounts of particulates, which must be removed before discharge into the atmosphere. Typical American practice is to burn the combustible gases in water-cooled hoods mounted above the BOF vessel, cool with excess air or water sprays, and pass the cooled gases through high-energy scrubbers or electrostatic precipitators. In most cases, the BOF vessels are equipped with open hoods that admit air for combustion of carbon monoxide on a relatively uncontrolled basis. If additional steam can be used in the plant, the combustion hood can be used as a steam generation device, although the steam production will only be cyclic.

In Japan, a closed-hood gas collection system known as the OG system is used, wherein the waste gases containing CO are scrubbed, collected, and used as fuel gas. The basic OG system is used at a few steel plants in the United States, but the CO-rich off-gas is burned in a flame stack rather than stored and used for fuel. A major advantage of the OG system, other than recovering a fuel gas, is the large reduction in the volume of waste-gas required to be handled by the scrubbing system.

Electric Furnace Steelmaking

Production of steel in electric-arc furnaces has grown rapidly since World War II and is currently estimated to be more than 15% of total steel production. Because of the phase-out of open-hearth steelmaking, the increase in BOF steel production, and the associated scrap-use limitation, the amount of steel produced in electric-arc furnaces is expected to increase even more.

The combustion of fossil fuels currently plays a very small role in electric steelmaking. This may change in the future as advances in technology permit the increased use of scrap preheating. Most authorities agree that scrap preheating will be accomplished outside the electric-arc furnace in a specially designed charging bucket, probably equipped for bottom discharge. Many of the designs use excess-air burners to limit flame temperature and minimize oxidation of the scrap. Associated air-pollution problems include particulates from dirty scrap, iron oxide, and oil vapors. The requirement for both incineration at or above 1400°F and particulate removal has caused shutdown of several scrap preheating installations because of economic considerations.

Direct Reduction

A number of direct reduction processes are currently in use to provide an alternative to the blast furnace in the production of feed material for steelmaking furnaces. Both batch and continuous processes are in use, involving such equipment as rotary kiln, counterflow vertical shaft, traveling grate-kiln, and multistage fluid bed. Various types of raw materials are processed, such as lump ore, oxide pellets, and beneficiated concentrate. The degree of metallization ranges up to 95%, and a highly metallized product can be charged to an electric melter without scrap addition. Prereduced charge can be used in the blast furnace and steelmaking equipment such as the BOF. Some advantages of direct reduction are —

- Lower capital requirements than for coke-oven blast-furnace ironmaking
- Reduced dependence on hot metal for steelmaking
- Consistent chemical analysis of the feed material to the steelmaking process
- Reduced dependence on scrap.

In the past, direct reduction plants in the United States have been associated with mini-steel plants which are not fully integrated. These plants are dependent upon a reliable supply of natural gas at a low price. Currently, both availability and price are adverse to the process and it seems doubtful that additional plants will be constructed. Natural gas consumption in the most efficient plant is in the range of 13 to 14 million Btu per ton of product; less efficient plants may require as much as 20 million Btu per ton.

Hot metal from the blast furnace is transferred to the steel-making furnace in large, refractory-lined vessels or ladles. These are also used for transferring molten steel to the various casting operations. The refractory linings of the vessels must be cured after replacement and preheated before each use. Typically, open-flame burners are used for this at a very low thermal efficiency. Fuel requirements for ladle drying and heating range from 200,000 to 400,000 Btu per ton of metal.

Ingot and Continuous Casting

After removal from the furnace, the steel is poured into ingot molds or transferred to the continuous caster. Forming steel into ingots is an intermediate step prior to further processing. The steel is cooled to a solid, whereupon the ingot mold is removed. The finished ingot can be sent directly onto additional processing or stored indefinitely to meet scheduling needs.

In the continuous-casting process, the ingot stage is bypassed, and the molten steel is placed into one or more streams or strands that are fed from a holding chamber called a tundish. The molten steel is transformed directly into slabs, blooms, or billets and cut to the desired length by a traveling torch. The continuous casting process eliminates intermediate ingot formation, along with the energy required to reheat the ingot prior to the formation of slabs, blooms, or billets. The amount of steel output produced by continuous casting is increasing.

Soaking pits are used to reheat ingots to rolling temperature (about 2340° to 2400°F for carbon steel). Ingots are charged at a variable temperature because of varying time intervals between ingot pouring and charging into the soaking pits, brought about by conflicts in rolling schedules or other delays. The amount of energy required for reheating ingots varies a great deal because of the temperature variation in heating a cold ingot and one at intermediate temperature levels.

Soaking pits are simple round-, square-, or rectangular-shaped refractory-lined chambers having a retractable cover. Several pits grouped together are referred to as batteries, having common flue ducts and a single recuperator and stack. Fuels used in soaking pits include mixed blast-furnace gas and coke-oven gas, mixed blast-furnace gas and natural gas-air, straight coke-oven gas, straight natural gas, and residual oil. Single, nozzle, or port-mixing burners are used, and the burners are used and designed to minimize the temperature gradient between the burner wall and the back wall of the pit. Problems in fuel utilization occur when changing from one fuel to another, particularly from gaseous to liquid fuels, because of major variations in flame length and heat-release profiles.

Mill operating practices have a major effect on soaking pit fuel economy. Among them are —

- Ingot charging temperature
- Percentage of cold ingots charged

- Pit loading
- Holding time at temperature.

Fuel requirements vary from 545,000 to 2 million Btu per ton. The national average fuel consumption in soaking pit operations is estimated at 1 million Btu per ton.

Good combustion control is essential for maintaining fuel efficiency in soaking pits. This includes temperature control-fuel input, pit pressure, and air/fuel ratio. Substantial fuel reductions can be obtained by installing recuperators on soaking pits now operating on cold combustion air. Improved recuperator design can deliver combustion air preheated to higher levels than the current range of 700° to 800°F. The potential for fuel reduction is about 15%, taking into account the large number of soaking pits operating with cold combustion air or inefficient recuperators.

Most of the fuel used by the steel industry in reheat furnaces is for slab, bloom, and billet heating. The evolution of the modern, continuous, reheat furnace has been forced by rolling-mill improvements, steel quality requirements, floor space limitations, and low-cost energy, toward the direction of increased heating rates and higher mean-effective-thermal head temperatures. Most of these furnaces are continuous-pusher types with the load supported on water-cooled skids over most of the furnace length and on a refractory hearth in a final soak zone, which is overfired. Both three-zone and five-zone furnaces are in use. More of the fuel input is progressively burned near the charge end to increase furnace capacity. As a result, flue-gas temperatures have increased, and this factor, as well as the heat lost to water-cooled surfaces, has resulted in increased fuel requirements per ton of steel heated. In recent furnace designs, the soak zone has been eliminated by using a walking-beam design, wherein the load is alternately supported on stationary and moving water-cooled supports. This furnace produces a uniformly heated product, without the cooler regions associated with the water-cooled support skids, and has the highest output per unit of floor space, but accomplishes this at the expense of fuel economy.

Average fuel consumption for reheat furnaces with preheated combustion air is in the range of 2.0 to 2.2 million Btu per ton for three-zone furnaces and 2.7 to 2.8 million Btu per ton for five-zone furnaces. Fuel economy for steel mill reheat furnaces is effected by furnace design, firing arrangement, heat losses, heat recovery, combustion and process controls, and operating practices. Although the furnaces are continuous, frequent delays at the rolling mill have an adverse effect on fuel efficiency and on the temperature uniformity of the product. Another important factor is the number of operating turns per week.

Estimates of total fuel requirements of steel mill reheat furnaces are frequently based on an average consumption value of 2.5 million Btu per ton of steel heated. Some of the rolled products may be reheated more than once, and, consequently, estimates of total fuel consumption for reheating range up to 300 trillion Btu per year.

Fuel conservation measures for reheat furnaces include those previously mentioned for soaking pits:

- Retrofitting recuperators to furnaces using cold combustion air or currently using inefficient recuperators
- Improved combustion control
- Improved operating practice
- Programmed input control.

Additional measures specifically for reheat furnaces include the following:

- Improved maintenance of skid rail insulation
- Control of air infiltration
- Increased temperature of preheated combustion air.

Emissions from soaking pits and reheat furnaces may include carbon monoxide and unburned hydrocarbons produced by inadequate or poorly maintained ratio controls. These can be eliminated by the installation of better equipment or by improving maintenance practices. The most significant emission will be NO_x, produced by the high flame temperatures required and combustion-air preheat.

Annealing, heat treating, and finishing operations follow in sequence the reheating and rolling mill operations. The major portion of the fuel used in the steel industry for annealing is for cold-rolled products in strip form. Approximately 35% of total United States steel production is in the form of strip and other cold-rolled products. Estimates of the amount of energy consumed for annealing, heat treating, and finishing operations range from 50 to 60 trillion Btu per year, including electricity. About one-half of this quantity is for annealing.

Fuels used for these processes are mainly natural gas and coke-oven gas. Natural gas is preferred because the sulfur content of a fuel has an adverse effect on product quality and on the maintenance of furnace alloy components.

Temperatures employed in heat-treating and finishing operations are much lower than those required in other types of process equipment and, consequently, NO_x levels should be correspondingly lower. Other emissions, such as carbon monoxide and hydrocarbons, are associated with the quality and maintenance of air/fuel ratio-control equipment. Many of the heat treating and annealing operations require the use of a protective atmosphere, primarily reformed natural gas. Disposal or leakage of protective atmospheres can result in locally high concentrations of carbon monoxide.

The equipment used in annealing, heat treating, and finishing operations includes the following:

- Batch and continuous coil and strip annealers
- Car bottom, roller hearth pusher tray, and other types of heat treat furnaces
- Tin-plating lines
- Galvanizing lines.

Some of the energy conservation measures being used on annealing equipment are —

- Conversion from radiant tube to direct firing
- Recuperation
- Improved combustion controls
- Use of ceramic fiber furnace linings, replacing brick refractories
- Substitution of nitrogen from oxygen plants for natural gas-based atmospheres.

Because of the relatively small percentage of total fuel use in this area and the low level of NO_x produced, any conservation measures adopted will not have a material effect on overall steel plant emission levels.

Trends in Process Modifications

Iron Making

Coke Ovens — Current and Near-Term

The major sources of emissions from coke ovens are the rapid evolution of steam when moist coal is charged, the discharge of gases and particulates from the charging openings, and the emissions during the coke push and subsequent quenching. Recent coke-oven battery designs have reduced the emissions to an acceptable level by predrying and preheating coal sized for pneumatic transport. Steam is used as the conveying medium and, with pipeline charging, the charging ports are sealed.

During the coking process, leakage from the push side and coke side door seals account for most of the emissions. New coke ovens feature improved door seals which reduce door leakage substantially.

New battery designs feature a hood over the coke side door to collect the emissions occurring during the coke push. The hood is ventilated and the gases conveyed to suitable air pollution control equipment. In another design coke is discharged to sealed container cars.

Emissions during coke quenching can be minimized by use of a process involving both wet and dry quenching on a continuous basis. Waste heat recovery can also be incorporated.

Hydrogen sulfide in the coke-oven gas is removed in some modern ovens by molten carbonate treatment. This process requires about 500 pounds of steam per ton of coke produced. The availability of better refractories has led to the design of batteries having wider and higher coking chambers, thus increasing productivity. Improved control over heat-release profiles is required and this is obtained by staged combustion and increased use of blast-furnace gas that contains a high percentage of inerts. This practice makes available to other steel mill furnaces a larger amount of coke-oven gas to replace natural gas or oil.

Coke Ovens — Long-Term

Dry coke quenching is claimed to improve the quality and yield of the coke produced and to achieve a major reduction in the emission of pollutants, as well as a potential for recovery of waste heat. The process is employed at several installations in Russia and uses counterflow shaft-furnace technology. Each quenching tower has a capacity of 90 tons per hour. A typical 3000-ton-per-day coke oven battery will require five quenching towers and will cost about $11 million. It is the general opinion of the American steel industry that significant dry coke quenching capacity will not be installed before 1985, although a demonstration plant might be in operation by 1980.

Some steel industry people think that the current replacement of existing coke-oven batteries by the modern coke ovens is the last "generation" to be installed. They expect that form coke or other types of compacted forms of calcined coal will take the place of coke ovens in the future, but not to a significant degree before 1990. Process off-gases yield the equivalent of coke-oven gas in total heating value, but have a lower heating value.

Sinter Plant — Current and Near-Term

Traveling-grate sinter lines are used to produce an agglomerate suitable for charging to a blast furnace from flue dust, coke breeze, fluxes, and other iron and carbon bearing particulates. Sinter lines are inherently a dirty operation and must be equipped with suitable stack-gas cleaning equipment to comply with emission regulations. Any combustible vapors in the stack gases present major problems because incineration requirements both increase overall fuel input and the stack-gas volume. This results in higher capital and operating costs for the emission control equipment, usually baghouses.

The economics of bringing the smaller and older sinter lines into compliance are unfavorable and, consequently, many of these are being shut down and removed. Some steel industry people think that sinter lines will be phased out altogether and replaced by alternative agglomeration processes, but others are currently installing very large sinter lines designed so as to avoid the major problems associated with the process. Some of these improvements are better seal designs to reduce air infiltration, improved seal maintenance, design of gas recirculating systems to reduce stack-gas volume and to eliminate carbon monoxide in the stack gases without incineration, and control over stack-gas temperature to prevent condensation in the baghouse.

Sinter Plant — Long-Term

Existing sinter plants cannot handle rolling mill scale, which is produced in large quantities, but is contaminated with rolling oil. The oil vapor is not removed by baghouses and passes to the exhaust stack as a pollutant. Consequently, the rolling mill scale is used as landfill, although it has a 71% iron content and could be a very good blast-furnace charge.

Both pelletizing and briquetting are under development and will, in the future, provide a hot-compaction process to replace sinter lines. These systems have a potential for handling rolling mill scale and for large reductions in both energy requirements and emissions.

Blast Furnace — Current and Near-Term

Because of the decreased availability of coking quality coal in the United States, major emphasis in recent years has been placed on increasing blast-furnace output and reducing the coke required per ton of hot metal. Some of the process and equipment modifications employed have been —

- Larger blast furnaces
- Higher blast temperature and oxygen enrichment
- Improved burden, pelletized and fluxed sinter
- Higher top pressure
- Improved blast-furnace stove designs and scheduling
- Auxiliary fuel injection, primarily oil and natural gas.

Increased cost and decreased availability of the auxiliary injection fuels have led to the development of systems for injection of pulverized coal or oil-coal slurries or emulsions.

The increased adoption of the basic oxygen process for steelmaking and the adverse hot metal-scrap ratio required for the BOF has made the capacity of some steel mills limited by the availability of hot metal. Additional mill capacity will require installation of new, modern blast furnaces and give the beneficial effect of increased dependence on coal. Additional reduction in coke consumption will be achieved by use of higher blast temperature, oxygen enrichment, and auxiliary coal injection.

Blast Furnace — Long-Term

The decreased availability of high quality coking coals will lead to a gradual adoption of processes for production of synthetic coke, such as form-coke, which can use high-sulfur, noncoking coals. The trend toward larger blast furnaces, higher top pressures, and additional improvements in burden will continue. If a satisfactory process for direct-reduction with coal-based fuels is developed, prereduced iron will probably become a major portion of the blast-furnace charge.

The development of efficient, dry-type, high-temperature, blast-furnace gas cleaning systems will make energy recovery by the use of off-gas turbines feasible.

Steelmaking

Open Hearth — Current and Near-Term

The use of open-hearth furnaces will continue to decline, both because of the higher production capabilities of the basic oxygen furnace (BOF) and also because of emission problems with existing open-hearth furnace designs. Steel mills with capacity limited by hot metal availability will continue to use open hearths because of greater flexibility in the hot metal-scrap ratio. These open hearths will be modernized so as to increase production rates and comply with emission control regulations. Increased use of oxygen roof-lancing to increase furnace output will probably occur. Increased NO_x emission may result.

Open Hearth — Long-Term

The use of open-hearth furnaces is expected to continue to decline and will probably amount to about 10% of total steel production by 1985.

Basic Oxygen Furnace (BOF) — Current and Near-Term

Use of BOF's for steelmaking will continue to grow because of the high productivity and favorable economics. The size of the BOF vessels is continuously increasing. A major advantage of BOF steelmaking is the very large reduction in dependence on external fuels. Only about 200,000 Btu per ton of steel produced is required for vessel dryout and preheating.

Preheating of the scrap fed to a BOF will reduce dependence on hot metal because only about a 68% hot-metal charge is required with the scrap preheated to 1200°F, whereas a 75% hot-metal charge is required with cold scrap.

The BOF carbon monoxide-rich off-gases have an average heat content of 250 Btu/CF or 400,000 Btu/ton of steel, and in most installations, the carbon monoxide is burned in the vessel, which produces a large volume increase in the stack gases flowing to the air pollution control devices. Some recent installations have been equipped with an OG collection system, which includes a sealed collection hood, two-stage venturi scrubbers, and a flare stack for carbon monoxide combustion. No information is available concerning the combustion efficiency of the flare stacks.

Submerged injection of oxygen has been successfully applied to BOF steelmaking and is expected to be used quite extensively in the near future.

Basic Oxygen Furnace – Long-Term

From both the energy conservation and pollution control points of view, recovery of the carbon monoxide-rich BOF off-gases will have a more attractive potential as the cost of purchased fuels increases and availability decreases. Economic considerations are the major inhibiting factors at the present time.

Development of improved scrap preheating systems with suitable emission controls will come about. The scrap preheating systems may be fueled by off-gas carbon monoxide.

Electric Furnace – Current and Near-Term

The use of electric furnaces for steelmaking will continue to grow, particularly in the nonintegrated steel mills. Some steel industry executives believe that future integrated plants will use a combination of BOF and electric steelmaking, giving maximum ability to vary the hot metal-scrap ratio. The productivity and efficiency of electric steelmaking will be improved by development of practical scrap-preheating systems.

Electric Furnace – Long-Term

Development of a coal-based process for direct reduction of iron oxide pellets or lump ore may bring about extensive use of electric melting of a prereduced charge.

Trends in Energy Utilization

The decreased availability and increasing cost of natural gas and low-sulfur oil has forced the steel industry to depend more on coal as the primary energy supply in the production of steel. A major trend in recent years has been to reduce the coke required per ton of hot metal because of the diminishing supply of coking coal. This has increased dependence on purchased fuels because of the reduced output of coke-oven gas. A current offsetting trend has been the increased use of BOF steelmaking, which requires more hot metal than the open hearth.

Part of the reduction in coke requirement has been achieved by injection of natural gas or oil at the blast-furnace tuyeres. The major injection fuel in the future will probably be powdered coal or high-sulfur oil, which cannot be used in direct combustion applications because of sulfur oxide emission regulations. Low-sulfur oil and coke-oven tar and pitch will probably be used for the more critical applications, such as soaking pits, reheat furnaces, and modernized open-hearth furnaces retained to provide hot metal-scrap flexibility.

Fuel cost, at least for the more critical heating applications, appears to have become secondary to fuel availability. Natural gas cost is currently in the $0.90 to $1.00 per million Btu range in the Chicago-Cleveland-Pittsburgh areas, and low-sulfur oil is estimated to cost $2.10 to $2.25 per million Btu at the burner. Many integrated steel plants are converting soaking pits and reheat furnaces to oil firing because the plants cannot obtain firm contracts for natural gas. Some of these companies will continue to use natural gas when it is available during the summer months.

Serious consideration is being given to the in-plant production of synthetic fuels from coal even though current estimates of cost are in the $3.00 to $4.00 per million Btu range.

One of the problems in assessing the effects of fuel availability, fuel cost, and changes in process technology is that most energy conservation estimates are based on overall energy requirements, including coal, rather than that for critical fuels such as natural gas and low-sulfur oil.

For example, on an overall energy basis, an integrated plant with BOF steelmaking requires more energy than one with open hearths because of the increased hot metal-scrap ratio. However, the requirement for purchased fuels will decrease by more than 3 million Btu per ton, and this decrease has the greater significance.

Future integrated steel plants can be designed to be independent of the need for purchased critical fuels by using both BOF and electric steelmaking for hot metal-scrap flexibility and continuous casting. The rate at which this objective can be met will be quite slow because of the large investment in existing facilities and enormous capital requirements for new plant construction. The slow rate of change is shown by the AISI estimate of the steel industry fuel consumption, by source, for 1972 and 1980:

Source	Year	
	1972	1980
Coal, %	67.3	68.5
Purchased Gas and Oil, %	28.8	26.9
Purchased Electricity, %	3.9	4.6
Btu X 10^6 per Net Ton Shipped	32.6	30.1

During the field interviews, various integrated steel plants reported the following energy consumptions, by source, for 1974:

Plant	A	B	C
		%	
Coal	75	60	70
Oil	10	22	5
Natural Gas	15	18	20
Purchased Electricity			4.7
Other			0.3

As indicated, general fuel-use trends in the industry will be to increase the relative amount of coal consumed per ton of steel shipped and to decrease dependence on purchased oil and gas. The amount of oil used compared with natural gas will increase because of the decreased availability of natural gas. Major shifts toward increased use of coal will require very large amounts of capital, both for new production facilities and for the associated emission control equipment.

The following list presents a more detailed view, by process, of the trends in fuel utilization.

Ironmaking – Current and Near-Term

- **Increased use of coal as a primary fuel, both in increased coke-oven output for blast-furnace injection and for boiler firing.**
- **Increased availability of coke-oven gas.**
- **Decreased use of coke-oven gas for under-firing coke ovens, partial replacement by increased use of blast-furnace gas.**
- **Coal and high-sulfur oil will be used as blast-furnace injectants.**
- **Use of natural gas as a blast-furnace injectant, for blast stove heating and other auxiliaries will decline sharply.**
- **Direct combustion of coal in pelletizing facilities, both traveling-grate and shaft types.**

Ironmaking – Long-Term

- **Coke ovens will be replaced, possible to a major extent, by form-coke or some other pyrolyzed coal product. Heating value of the gas output may be much less than that of coke-oven gas, possibly less than 200 Btu/CF.**
- **Coal gasification plants producing low-Btu gas may be installed in steel mills or the product gas made available from a nearby source.**
- **Heating value will be in the 175 to 300 Btu range, depending on the process used. This gas may be a good blast-furnace injectant if the economics are favorable.**
- **Direct reduction to a highly metalized iron product using solid reductants may replace part of the coke oven-blast furnace ironmaking capacity. The availability of low-sulfur fuels at a competitive price will be essential and appears to be doubtful at the present time.**

Steelmaking – Current and Near-Term

- **Use of oil, natural gas, or in-plant gases for steelmaking furnaces will continue to decline as additional open-hearth furnaces are replaced by BOF and electric furnace steelmaking.**
- **Use of natural gas as an open-hearth fuel will decline sharply, replaced by oil or coke-oven by-products.**

Steelmaking – Long-Term

- **Recovery of carbon monoxide waste gas from BOF steelmaking and possibly using it to preheat the scrap charge.**
- **Development of direct reductive processes using solid reductant.**

- Application of nuclear energy to steelmaking with availability of reducing gases for direct reduction or blast-furnace injection.

- Development of continuous steelmaking.

Soaking Pits and Reheat Furnaces — Current and Near-Term

- Shift from natural gas and coke-oven gas to oil firing or blast-furnace gas and other coke-oven by-products.

- Fuel conservation by use of techniques previously discussed.

- Increased use of induction heating for slabs and billets.

- Increased use of continuous casting.

Soaking Pits and Reheat Furnaces — Long-Term

- Use of coal, solvent refined coal or a slurry, or emulsion of oil and solid fuel.

- Major reduction in fuel requirements by development of a process for production of steel strip directly from molten steel.

Heat-Treating and Finishing Operations — Current and Near-Term

- Available natural gas and coke-oven gas conserved in other mill areas will be used.

- Some installations will be converted to oil firing. In most cases, distillate oil will be required because of sulfur limits.

- Gas atmospheres produced from natural gas will be replaced to a large extent by by-product nitrogen from captive oxygen plants.

- Electric heating will replace natural gas in cases where alternatives are not feasible.

Trends in Emissions

In most cases, those interviewed were not disposed to discuss specifics of emission control problems except to state that every effort is being made to comply with local standards at very heavy costs. In many cases, attention was drawn to the large energy requirements for compliance with future standards, particularly those for fugitive emissions and building evacuation.

It was generally agreed that not much is known about NO_x emissions from steel-mill equipment. In one case, concern was expressed that flare-stack combustion of carbon monoxide might not be effective. Another concern was that baghouses and precipitators or scrubbers are not effective in the elimination of oil vapor from oily scrap. Combustion of such vapors or carbon monoxide adds greatly to the volume of gases handled in demonstration cleanup devices.

Major combustion-related emission problem areas were given as —

- Coke ovens
- Sinter lines
- Open hearth
- BOF and electric furnace
- Acid recovery from waste pickle liquor.

Data Analysis

The emission of pollutants from iron and steel process equipment involved in direct combustion of fossil fuels includes carbon monoxide, nitrogen oxides, sulfur oxides, and unburned hydrocarbons. Particulates result from the direct combustion of coal, but are mostly present in flue products as fine particulates picked up from process materials. Unburned hydrocarbons usually occur as the result of inadequate or improperly adjusted combustion controls. Sulfur oxides are formed primarily from process materials containing sulfur and secondarily from fuel sulfur and cannot be controlled by modifications in direct combustion technology. Carbon monoxide can result from improper adjustment of combustion controls, but in the iron and steel industry the major sources are the blast furnace, sinter and pellet lines, and steelmaking furnaces.

The primary sources of nitrogen oxides are chemically bound nitrogen in the fuels and that formed in flames at high temperature by combination of active species of nitrogen and oxygen. The latter type is strongly affected by combustion process modifications, and, in the case of utility power boilers, substantial reductions ranging up to 90% have been achieved. The modifications used have included flue-gas recirculation, staged combustion, excess air control, water injection, fuel-air mixing rate control, and internal recirculation.

Steel companies do not, in general, appear to have much specific knowledge concerning emissions of nitrogen oxides from process equipment, except that from boilers. Some concern was expressed about future regulations concerning

NO_x emissions and the state-of-the-art concerning emissions from specific types of process equipment and means for control.

The most frequently expressed concern was about the high energy input required for emission control equipment and the corresponding adverse effect on the ability to meet energy conservation goals. This concern was reflected in a request by several of the steel companies for R&D programs to develop emission control systems requiring less energy input.

Several types of process equipment in use involve collection of process off-gases with a substantial carbon monoxide content. Direct combustion or incineration as a control technology increases the volume of gases discharged to emission control equipment thus increasing capital cost, operating cost, and the energy requirements for emission control. The sealed collection hood system developed by the Japanese (OG system) for basic oxygen furnaces prevents or minimizes the infiltration of air at the collection point. The collected gases are cleaned and used as auxiliary plant fuel. In American installations using this system, the cleaned off-gases are flared. The effectiveness of flare stacks in burning carbon monoxide was questioned by some steel industry representatives. The logical end use for BOF off-gas is for preheating the scrap charged to the furnace, but up to the present time both technical and economic considerations have prevented such use.

The emission of nitrogen oxides from iron and steelmaking and processing equipment does not appear to have been extensively investigated. However, reasonable estimates can be made by assuming a relationship between known operating temperatures and NO_x concentration in stack gases. This relationship is affected by other variables, such as combustion air preheat temperature and oxygen enrichment of combustion air.

Table 3 shows the estimated NO_x concentrations for the major energy-intensive processes and the resulting total annual combustion-related NO_x production based on 1971 steel production energy consumption data.

Pelletizing

Pelletizing is carried out at or near the iron mines because low-grade ores are used and ore beneficiation precedes the pelletizing operation. The beneficiated product is extremely fine and would be very difficult to handle and transport to the steel mills. The cost of shipping unbeneficiated ore would

Table 3. ESTIMATED NO_x EMISSIONS FROM STEEL-MILL PROCESSES AND EQUIPMENT

Process or Equipment	Fuel Consumption, 10^{12} Btu/yr*	NO_x Emission Level, ppm	Tons NO_x/ 10^{12} Btu	Tons NO_x/yr
Pelletizing	27	300	210	5,670
Sintering	93	500	350	32,550
Coke Oven Underfiring	212	200	140	29,680
Blast Stove Heating	200	100	70	14,000
Open-Hearth Furnace	127	600	420	53,340
Soaking Pit and Reheat Furnaces	510	300	210	107,100
Heat Treating and Finishing	60	200	140	8,400

* Basis: 1971 steel industry data.

be almost double that of the beneficiated and pelletized product. Previous IGT studies have shown that pelletized ore production will be about 60 million tons/yr by 1985. The fuel consumed by the pelletizing furnaces has remained about constant at 600,000 Btu/ton. This indicates that total NO_x emission from pelletizing furnaces will reach about 8500 tons/yr by 1985. The steel industry and equipment builders are considering coal firing the pelletizing furnace combustion chambers. If this is done, it will probably bring about an increase of about 50% in NO_x emission.

Sintering

The use of sinter machines to agglomerate ore fines, flue dust, and coke breeze has been declining since 1966 and amounted to 43 million tons in 1971. If the present rate of decline continues, the 1985 production of sinter would be about 27 million tons. The attitude of the steel industry is mixed because many steel plants are phasing out sinter lines, while at least one major producer has replaced several small sinter lines with a large machine designed to meet pollution control regulations. In either case, the NO_x output will continue to be a major pollutant, if our estimates are correct.

Coke-Oven Underfiring

Although the current practice of firing coke ovens with a mixture of blast-furnace gas and coke-oven gas and slow mixing in the combustion chambers should tend to minimize NO_x production, the estimated total is quite large because of the large quantity of fuel consumed.

The reduction in the coke required per ton of hot metal achieved during the 1960's will continue, but steel mills are currently installing new coke ovens because of the increased need for hot metal due to the high BOF hot metal-scrap ratio. The 1985 projection for coke-oven underfiring fuel is 458 trillion Btu. If the NO_x concentration remains constant, the resulting total emission of NO_x will reach 64,120 tons.

Although it is reasonable to assume that substitution of form coke may result in a substantial reduction in NO_x production, the general opinion in the steel industry is that form coke will not be a significant factor in 1985.

Blast-Stove Heating

As in the case of coke-oven underfiring, the blast stoves require very large quantities of fuel for heating. However, since the stoves are heated primarily with blast-furnace gas (80 to 95 Btu/CF) the NO_x concentration is lower due to the presence of diluents and a low flame temperature.

The projected need for hot metal in 1985 is 124 million tons. This amount of hot metal will require 280 trillion Btu for blast-stove heating. Assuming no reduction in NO_x stack-gas concentration, the NO_x emission in 1985 will be 19,600 tons/yr. Because of the low estimated NO_x concentration and the presence of inerts in the fuel gas, equivalent to flue-gas recirculation, the potential for NO_x reduction is probably small.

Open-Hearth Furnace

NO_x emissions from open-hearth furnaces are very high because of the high combustion air preheat temperature, high operating temperature, and the use of oxygen lances to increase production rates. The data available and our estimating technique indicate that NO_x concentration will be in the 600- to 800-ppm range. Although many open hearths are being phased out because of emission control difficulties and better economics of steel production with the BOF process, several steel mills are modernizing open-hearth shops, including pollution control equipment to provide flexibility in the hot metal-scrap ratio, particularly those mills with a hot-metal deficiency. Therefore, predictions that the open hearths will be phased out entirely by 1985 are unrealistic, and it is anticipated that about 15 million tons will still be made by the open-hearth process in 1985. Fuel consumption has been decreasing and may reach 2.5 million Btu/ton in 1985. This will require a fuel consumption of 37.5 trillion Btu for open-hearth steel production and result in an NO_x emission level of 15,750 tons.

Soaking Pits and Reheat Furnaces

These are large furnaces with fuel inputs ranging from 1.0 to 3.5 million Btu/ton heated. Fuel efficiency is affected by many factors such as furnace size, design, combustion controls, combustion air temperature, furnace scheduling, and downtime. Improved efficiency measures, which do not increase flame temperature, will, in general, reduce NO_x emission in proportion to the reduction in fuel usage.

Existing fuel-conservation measures in soaking-pit heating include improved scheduling so as to charge at a higher ingot temperature, programmed input control, improved burner designs, air/fuel ratio control responsive to stack-gas oxygen content, addition of recuperators to existing cold combustion air installations, and use of recuperators designed to give higher preheat temperature. Of these, the use of high-mixing-rate burners and an increase in combustion air preheat are likely to increase the NO_x emission level. At the present time, only experimental information is available concerning the effect of these parameters on NO_x levels.

Soaking-pit and reheat-furnace operating temperatures are such that the estimated NO_x levels should fall in the 250 to 350-ppm range. However, the very large amounts of fuel used result in a total NO_x output estimated at 107,000 tons in 1971.

A major factor that will reduce consumption of purchased and in-plant fuels and thereby decrease NO_x output is the trend toward use of continuous casting. In this process, finished shapes are produced from molten steel, thus eliminating soaking pits and most of the reheat requirement. About 20% of total steel production, or 40 million tons, is estimated to be produced by continuous casting in 1985. In spite of this, soaking-pit and reheat-furnace steel capacity will have to be increased during the 1975 to 1985 period to provide for the expected growth in steel production. According to the IGT projection, conventional steel processing will account for 160 million tons in 1985. At the present fuel consumption of 4.7 million Btu/ton, the total fuel consumed for soaking pits and reheat furnaces in 1985 will be 750 trillion Btu. This fuel consumption will result in an estimated NO_x emission of 157,900 tons.

Heat-Treating and Finishing Operations

This category includes annealing, hardening, carburizing and normalizing of most of the steel industry cold-rolled products, as well as production of coated products. Fuel consumption in 1971 was about 600 trillion Btu for the production of cold-rolled products (about 25% of total steel production). NO_x emission levels are assumed to be in the 150 to 250-ppm range. On this basis, total NO_x emission in 1971 for this category will be about 8400 tons. Assuming that production of cold-rolled products remains at about 25% of total steel production, the 1985 NO_x emission will amount to 11,200 tons/yr.

Recommendations

This program is concerned with air pollutant emissions from combustion processes and the control of these emissions by combustion modifications. The iron and steel industry has assembled a list of recommended programs for dealing with the problems of energy utilization efficiency and air pollutant emissions. However, most of these recommendations involve means other than combustion modifications and thus fall outside the scope of this program.

Recommendations for General Emission Control and Energy Conservation According to the Industry

- Development of stack-gas and air emission control devices requiring less energy input.
- Development of means other than incineration for emission control of carbon monoxide and oil vapors.
- A study of the interrelationship between energy use and pollution control in new steel plants, where energy self-sufficiency is now a major objective. The capital requirements to meet these objectives are now almost prohibitive.
- Systems for conversion of low-temperature-level stack and other heat losses to a useful form.
- Design, construction and operation of a 3000 ton/day form-coke demonstration plant.
- Design, construction, and operation of a 3000 ton/day coke dry-quenching plant.

- Development of an improved process for desulfurization of coke-oven gas.
- Development of an improved process for treatment of coke-oven water discharge, particularly for cyanide removal.
- Completion of the development of a system for injection of coal at the tuyeres of blast furnaces.
- Development of a process for hot-briquetting of in-plant fines to replace sinter lines.
- Development of a process for agglomeration of mill scale.
- Development of an air-recirculating system for sinter lines to reduce the volume of stack gases requiring emission control.
- Development of practical means for control of carbon monoxide in sinter lines.
- Development of processes for practical control of NO_x from steelmaking processes.
- Development of processes for practical collection or suppression of oil vapors from charging of oily scrap in electric furnaces and BO vessels.
- Determination of the effectiveness of flare-stack disposal of carbon monoxide from BO vessels.

Recommendations Based on Evaluation of Data Collected During Program

The major pollutants that can be affected or controlled by combustion technology are carbon monoxide, unburned hydrocarbons, and nitrogen oxides. Sulfur oxides and particulates come from materials in the process and the fuel itself and usually cannot be reduced by combustion technology. Many of the listed research or development recommendations by the steel industry are undoubtedly worthy of consideration, but are not amenable to control by combustion modifications and are, therefore, not within the scope of this investigation.

There does not appear to be much specific information available on NO_x produced by steel mill process equipment, particularly the types operating at high-temperature levels. The important types would be pelletizing-furnace combustion chambers, open-hearth furnaces, soaking pits, and large reheat furnaces.

We recommend that a field investigation be undertaken to determine the NO_x emission levels from the listed types of equipment. Following this investigation, or possibly concurrent with it, we also recommend a modification program to determine the effectiveness in NO_x reduction of the techniques already in use on power boiler firing such as:

- Reduced excess air
- Staged combustion
- Stack-gas recirculation
- Aerodynamic control over mixing and recirculation.

Glass Industry — Current State-of-the-Art

The glass industry can be broken down into three segments, based on the type of glass produced. The largest segment is the container glass industry, which produces about 64% of the total amount of glass (by weight) produced by the entire industry. The next largest segment, pressed and blown glass and glassware, produces nearly 21% of the total amount manufactured by the entire industry. The third segment is the flat glass industry, which produces about 15% of the total industry output.

While the specific processes used within each segment of the industry vary according to the product being manufactured, glass manufacturing involves three major energy-consuming processes: melting the raw materials, refining the molten glass, and finishing the formed products (Figure 1). Typically, about 80% of the energy consumed by the glass industry is for melting and refining, 15% is for finishing, and 5% is for mechanical drives and conveyors. The primary differences in processes used among the various segments occur in the refining and finishing operations.

Melting

Melting practices are essentially the same throughout the glass industry, regardless of the end product. The first step is the preparation of the raw glass batch. In this step, the various raw materials, such as sand, limestone, soda ash, and various minor ingredients (fluxes, colorizers, and decolorizers) are weighed in a batch hopper and dumped into a mixer. Water is usually added at this point and everything is thoroughly mixed. The material is transferred to a storage hopper, from which it is charged into the furnace. The energy consumed by this process is electrical and is used to drive the mixers and conveyors.

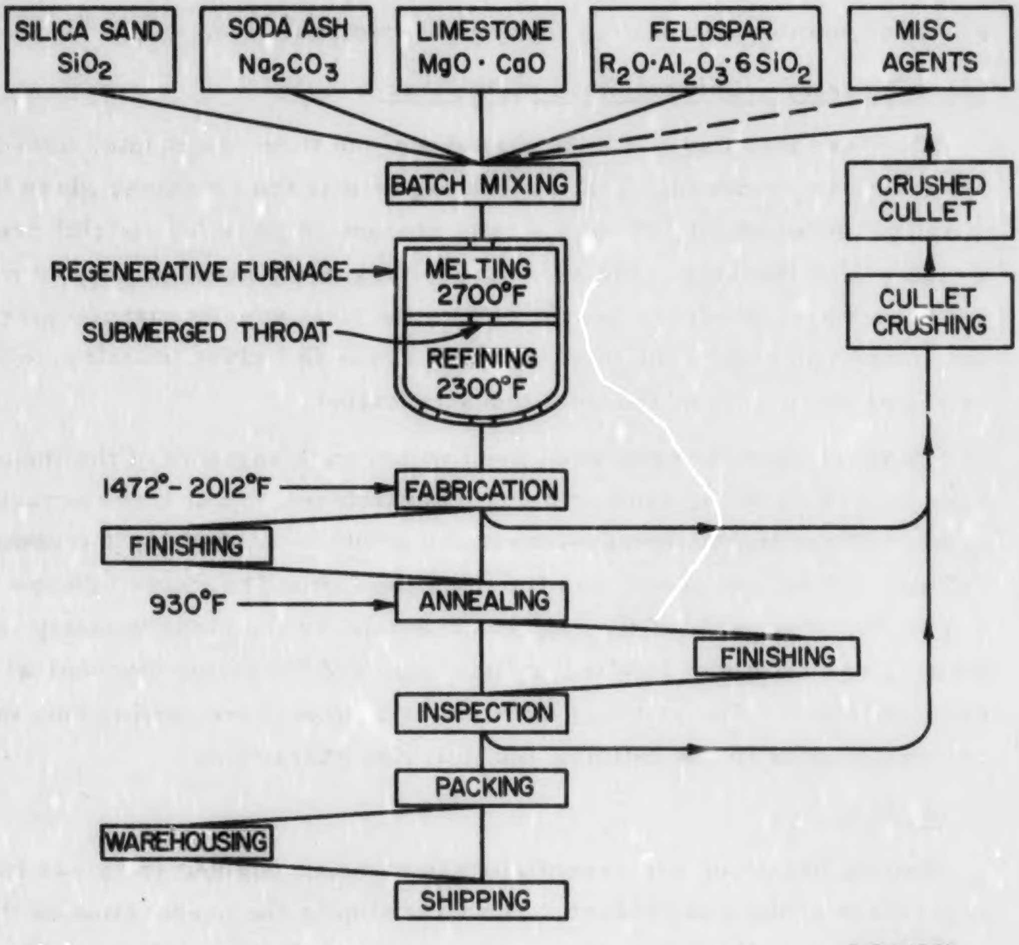
SILICA SAND
SiO_2
SODA ASH
Na_2CO_3
LIMESTONE
$MgO \cdot CaO$
FELDSPAR
$R_2O \cdot Al_2O_3 \cdot 6SiO_2$
MISC
AGENTS
BATCH MIXING
CRUSHED
CULLET
REGENERATIVE FURNACE
MELTING
2700°F
SUBMERGED THROAT
REFINING
2300°F
CULLET
CRUSHING
1472° - 2012°F
FABRICATION
FINISHING
930°F
ANNEALING
FINISHING
INSPECTION
PACKING
WAREHOUSING
SHIPPING
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Figure 1. FLOW DIAGRAM FOR SODA-LIME GLASS MANUFACTURE

The second step is the actual melting of the glass batch. The mixed raw materials are mechanically charged through a port, known as the "doghouse," into the melter. Most of the melters in use within the industry are continuous reverberatory furnaces equipped with checker-brick regenerators for preheating the combustion air. Some unit melters are also in use at a savings in investment cost but at a substantial sacrifice in fuel-utilization efficiency.

Reverberatory furnaces in this industry break down into two classifications according to the firing arrangement used: end-port and side-port melters. In the operation of a side-port-fixed furnace (Figure 2), the preheated combustion air mixes with the fuel in the port, resulting in a flame that burns over the glass surface. The products of combustion exit via the opposite port, down through the checker-bricks, and out through the reversing valve to the exhaust stack. Typically, there are several ports situated along each side of the furnace. In contrast, there are only two ports in an end-port-fired furnace (Figure 3), located on the rear wall of the furnace. The flame is ignited in one port, travels out over the glass toward the bridgewall, and "horseshoes" back to the exit port — the other port in the rear of the furnace. In both types of furnaces, the firing pattern is reversed every 20 to 30 minutes, depending upon the specific furnace. During this reversal period, the flame is extinguished, the furnace is purged of combustion gases by reversing the flow of combustion air and exhaust gases passing through the reversal valve, and combustion is then reestablished in what was previously the exhaust port. Both types of melters are operated continuously throughout a campaign that normally lasts 4 to 5 years, at sustained temperatures up to 2900°F.

In addition to the reverberatory-type melters, day tanks, unit melters, and pot melters are used, mostly in the pressed and blown glass industry. Many of these melters are batch-type, as opposed to continuous, resulting in a substantial reduction in fuel-utilization efficiency. Much of the fuel that is wasted is due to the antiquated methods of operation and associated equipment used with these melters.

From the melter, the molten glass passes through a refractory-lined throat into the refinery. The refinery may be an integral part of the melter, separated by the bridgewall, but taking its heat secondarily from the melter, or the refinery may be a separate entity. In the latter case, the refiner is equipped with auxiliary burners. The purpose of the refining step is to allow

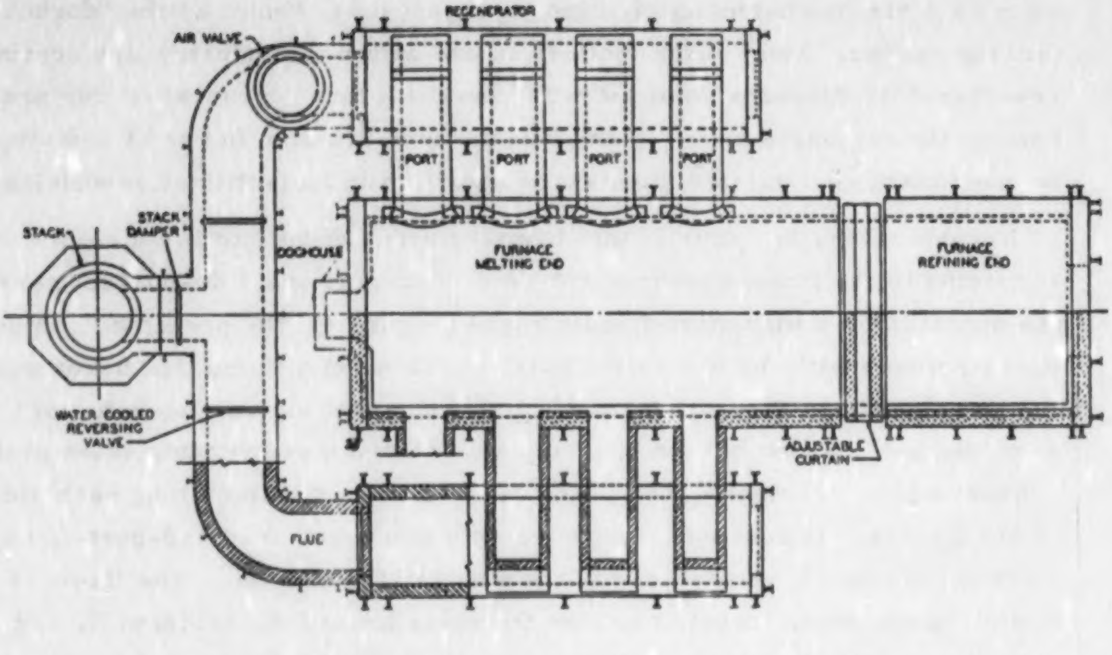
REGENERATOR
AIR VALVE
PORT
PORT
PORT
PORT
STACK
STACK DAMPER
DOGHOUSE
FURNACE MELTING END
FURNACE REFINING END
WATER COOLED REVERSING VALVE
ADJUSTABLE CURTAIN
FLUE

Figure 2. PLAN VIEW OF SIDE-PORT, FLAT GLASS FURNACE

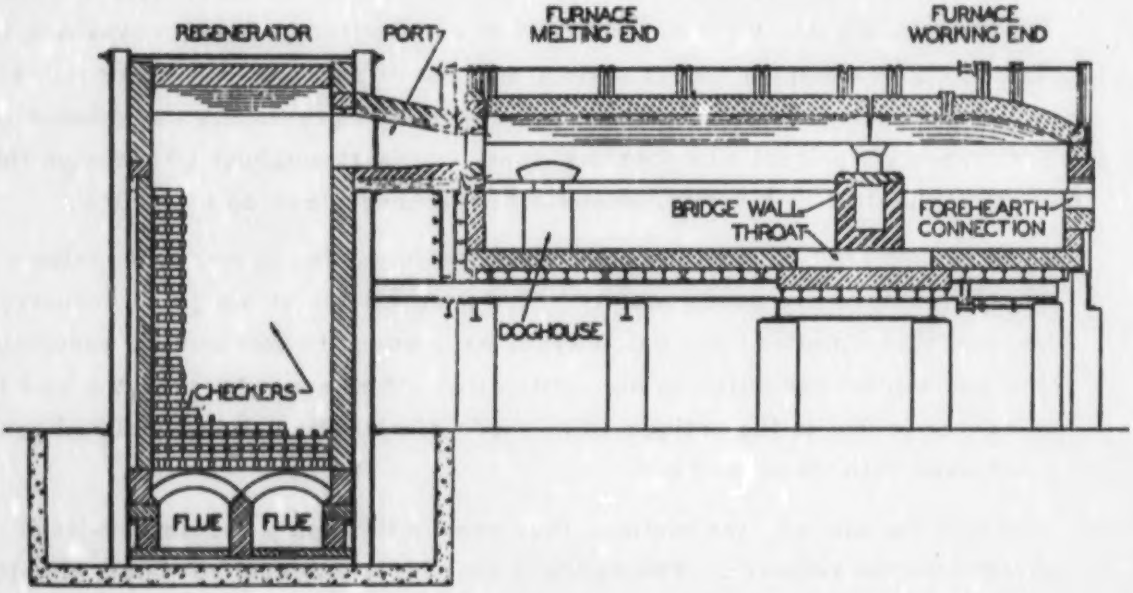
REGENERATOR
PORT
FURNACE MELTING END
FURNACE WORKING END
BRIDGE WALL
THROAT
FOREHEARTH CONNECTION
DOGHOUSE
CHECKERS
FLUE
FLUE

Figure 3. LONGITUDINAL SECTION OF TYPICAL END-PORT FURNACE

the gas bubbles trapped in the molten glass to escape and to reduce the temperature of the glass to a workable range. Upon completion of the refining step, the molten glass is ready for processing.

Finishing

Within the process of finishing, there are the fabrication and annealing steps. The specific processes used within each step depend on the product that is being made. This, in turn, will determine the energy requirements for the entire finishing process.

Fabrication

Product fabrication within the container-glass industry is relatively straightforward, with minimal variation from one process to another. The two primary processes in use for container fabrication are the Owens process and the flow process. In the Owens process, conditioning of the glass prior to forming takes place in pots. In the flow process, conditioning occurs in the forehearth and feeder. In both cases, a small amount of energy, usually natural gas, is consumed to bring the glass to the temperature required for forming.

After the glass has been properly conditioned, it is fed into a forming machine. The machines used in the two processes vary and for purposes herein are not significant. The energy consumed by the machines is electrical and is required not only to drive the machines, but also to drive compressors to obtain the required compressed air for blowing.

Product fabrication within the flat-glass industry varies according to the type of glass (sheet, plate, or float) produced. Sheet glass is produced by one of several continuous processes in which the glass is drawn vertically out of the drawing chamber that contains the properly refined and conditioned molten glass. The surface of the product made in this manner, although slightly wavy in appearance due to variances in viscosity, is very brilliant and thus requires no polishing.

Plate glass, in contrast to sheet glass, is rolled. Furthermore, the glass is not "finished" upon exit from the rolling operation. Rather, a substantial amount of grinding and polishing is required to produce the smooth surface needed for quality purposes. Because of the sizable investment that must be made to install a grinding and polishing operation, the float-glass process has been developed, which produces superior quality plate glass without grinding and polishing.

In the float-glass process, the molten glass flows from the melting chamber into a float chamber, which is a molten tin pool. As the glass flows over the molten tin, it assumes the smooth and perfectly flat surface characteristics of the tin surface, along with uniformity of thickness. The tin is maintained in the molten state with electric heating elements. Oxidation of the tin is prevented by the use of a controlled atmosphere. In terms of energy utilization, the float-glass process reduces the amount of energy consumed for power. However, it is not clear whether the overall process consumes less energy than the typical plate glass production line.

Annealing

After the glass has been formed into its final shape, it must be cooled to room temperature. In order to prevent strains from occurring, the glass is annealed, a process whereby the temperature is controlled and gradually reduced. Figure 4 shows a typical annealing cycle for a controlled recirculation lehr. While the actual cooling cycle varies from one type of glass to another, the annealing procedure is essentially the same for all types of glass. The glass is placed on a continuous conveyor and passed through a tunnel-type oven, called a lehr, which is zoned so that the cooling curve precisely matches that required to obtain a strain-free product.

The annealing lehrs can be heated by convection, radiation, or a combination of both. The most effective method is to use zoned, convection lehrs with internal distributors to obtain lateral temperature uniformity. These require external fans and heater boxes, but have the advantage that both gaseous and liquid fuels can be used to heat the recirculated air. Some lehrs are direct-fired by atmospheric or premix burners or by excess-air burners. Compared with the melting and firing processes, energy consumption is relatively low.

Inspection

The final phase of the finishing operation is the inspection of the finished product. Glass that does not meet the quality standards is recycled back to the melter and remelted. The amount of glass recycled varies considerably, but a good approximation is 10% to 12% of the total glass production. While

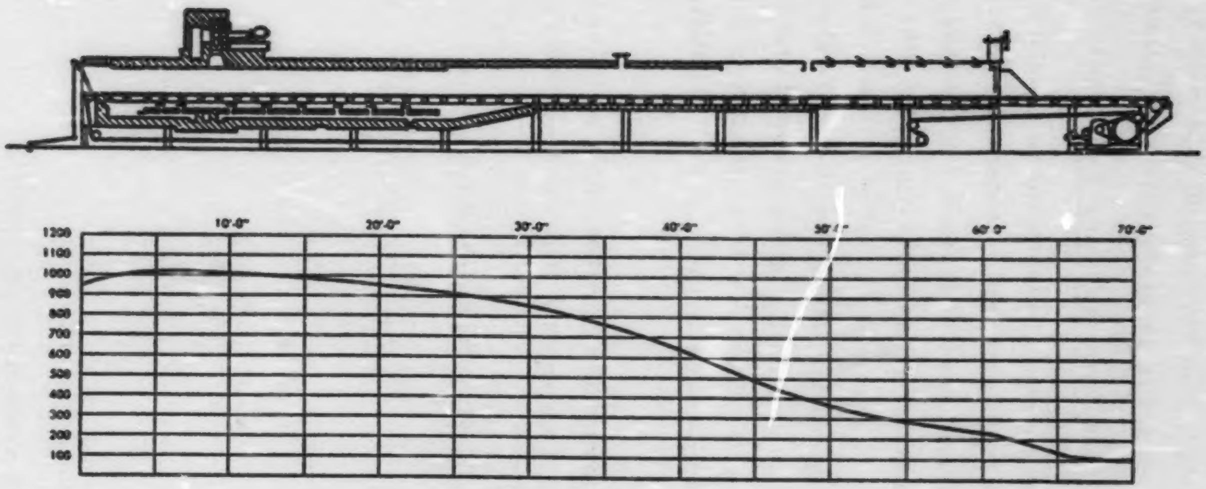

Figure 4. TYPICAL ANNEALING CYCLE FOR A CONTROLLED RECIRCULATION LEHR

remelting requires additional energy and would thus seem undesirable, in fact, remelting consumes less energy than melting of the batch material. Thus, adding cullet, as the recycled glass is called, to the raw batch lowers the amount of energy required for melting the batch. The energy consumed for remelting is included with the energy used for the melting process and is not considered separately. For purposes of this report, there are no other major combustion-related uses of energy in the glass industry.

Energy Utilization in Glass-Manufacturing Processes

Glass melting is the major energy-consuming process in the glass industry. Efficiencies of continuous melters vary considerably, depending upon basic design as well as furnace age, type of glass being melted, and the end use of the product. In the container glass industry, most glass companies claim to operate at a fossil-fuel consumption level of 4.0 to 7.0 million Btu/ton of glass melted. In the flat glass industry, fossil-fuel consumption is 6.0 to 12.0 million Btu/ton of glass melted. In the pressed and blown glass industry, fossil-fuel consumption varies from 6.0 to 40.0 million Btu/ton of glass melted, and many companies consume between 30.0 and 40.0 million Btu/ton of glass melted.

Note that these fuel consumption figures apply to furnaces during melting operations. However, data on energy utilization (Table 4) indicate that

Table 4. BREAKDOWN OF ENERGY CONSUMPTION BY THE GLASS INDUSTRY IN 1971*

	Flat Glass (SIC Code 3211)	Containers (SIC Code 3221)	Pressed and Blown Glass (SIC Code 3229)	Total
Glass Produced, 10^6 tons	2.56	10.90	3.50	16.96
Energy Consumption, 10^{12} Btu				
Melting	44.7	104.3	50.5	199.5
Annealing	8.4	19.6	9.5	37.5
Other	2.8	6.5	3.2	12.5
Total Energy Consumption, 10^{12} Btu	55.9	130.4	63.1	249.4
Average Energy Consumption for Melting, 10^6 Btu/ton of glass	17.5	9.6	14.4	11.8
Average Energy Consumption for Entire Production, 10^6 Btu/ton	21.8	12.0	18.0	14.7

* Excludes energy consumed for electricity generation.

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energy consumption is actually higher because operation is suspended for breakdowns and holidays many times during the year. During these periods, the furnaces are idled to maintain furnace temperature while production stops. Thus, energy is consumed but no glass is produced, thereby increasing the overall average energy consumption per ton of glass produced. An even greater source of discrepancy is the variation in the amount of cullet used from one glass plant to the next. The amount of cullet charged varies from 10% to 30% of the total raw material charged to the melter. As previously stated, lower percentages of cullet charged result in higher fuel consumption. In general, economic considerations prevent higher percentages of cullet from being charged.

These figures indicate that the container glass melters are operated most efficiently. The glass in the flat glass industry is of higher quality than that in the container glass industry; thus, gas bubbles (seeds) and unmelted raw batch (stones) cannot be tolerated. Consequently, furnaces in the flat glass industry* are very large compared with other glass industry furnaces to allow for the long soak periods required to remove all impurities such as entrapped gases and solid batch particles. In the container industry, the furnaces are smaller, and shorter retention times are used because glass quality is not so critical. Over the length of a campaign, fuel consumption is independent of the type of furnace used – i. e., end-port on side-port fired.

Electric melters require less energy to melt a ton of glass than fuel-fired melters. However, if the energy, which is usually fossil fuel, used to generate the electricity also is considered, total energy consumption per ton of glass is higher than for fuel-fired melters. Typically, an all-electric melter requires about 2. 9 million Btu to melt a ton of glass; this is a melting efficiency of about 65%. But the fuel that is consumed to generate this electricity is about 8. 7 million Btu, based on a 30% efficiency of generation. Consequently, the "real" amount of energy consumed to melt glass in an all-electric melter is 8. 7 million Btu/ton.

In the pressed and blown glass industry, glassware is made by machine and by hand. The furnaces vary from the large continuous type to small pot furnaces. As a result, energy consumption per ton of glass produced varies widely.

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* Perhaps 8 sq ft of melting area per ton of glass melted per day in the flat glass industry versus 4 sq ft of melting area per ton of glass melted per day in the container industry.

The type of glass being melted also affects the energy consumption of a furnace. For example, glass color affects furnace efficiency. Most of the heat transferred to the glass from the flame and refractories is by radiation. However, as the color of glass changes, its absorptivity also changes. Consequently, certain colored glasses actually receive less heat from a given flame than others. Glasses that contain a high percentage of silica (90% and above) generally require very high melting temperatures (3000°F). Consequently, energy consumption is quite high. However, very little of this glass is produced because of the expense involved in building and operating a facility at these high temperatures. Soda-lime glass, which melts at considerably lower temperatures (2500°F), is the most commonly melted glass. Theoretical energy requirements are about 2.0 million Btu/ton of glass melted. Other types of glasses that are manufactured in the United States are borosilicate, lead silicate, and aluminosilicate. All these glasses require more than 2.0 million Btu/ton to melt. However, the changes in glass composition that normally occur during mixing of the raw materials are not likely to cause changes in energy consumption.

Approximately 15% of the total energy consumed by the glass industry is for annealing. Annealing-lehr efficiency is difficult to determine: It varies depending upon many factors, but is generally about 25%. Efficiency is affected by such factors as incoming glass temperature, lehr design, glass loading pattern and burner operation. The leakage of unwanted cold air into the lehr and the loss of heated air through unwanted openings also contribute to cause lower than desired operating efficiency.

Recently constructed annealing lehrs are equipped with radiant gas burners that eliminate open burning of natural gas in the lehr. These lehrs are generally more efficient than the older ones. As previously indicated, natural gas is the preferred fuel for annealing from the point of view of glass quality, economics, and efficiency of utilization. Oil can only be used in indirectly fired lehrs since direct firing would result in discoloration of the final product. Electricity is also used, but is more costly in terms of energy cost and equipment.

Air Pollutant Emissions in the Glass Industry

In addition to being the primary energy consumer in the glass industry, the glass-melting furnace also is the primary source of air pollutant emissions. The primary emissions are particulates, sulfur oxides (SO_x, sulfur dioxide, and sulfur trioxide), nitrogen oxides (NO_x, nitric oxide, and nitrogen dioxide), and carbon monoxide. Hydrocarbons are not a problem if proper combustion conditions are maintained. Table 5 summarizes the emissions from several glass melters as measured by a number of investigators.

Factors Affecting Air Pollutant Emissions

Several factors influence the emission rate of particulates from a glass-melting furnace, including batch composition, batch preparation, and type of fuel. The production rate of the furnace also is a factor.

Measurements of stack emissions from a glass melter have shown that the particulates emitted are primarily sodium sulfate, which is a minor ingredient of most glass batch. In the furnace, it vaporizes and decomposes to form elemental sodium and sulfate.[5] When these gases pass through the checker-brick and are cooled, sodium sulfate is re-formed. Only about 40% of the sodium sulfate charged into the furnace is vaporized; the remainder goes into the glass. In addition to the sodium sulfate, a small amount of raw batch that is carried out of the furnace by the flue gases is emitted. This emission can be minimized by proper batch preparation, which consists primarily of wetting the material before charging it into the furnace.

The amount of SO_x emitted from a furnace depends on 1) the sulfur content of the fuel and 2) the amount of sulfur-bearing compounds in the raw materials. Consequently, natural-gas-fired furnaces generally exhibit lower SO_x emissions than oil-fired furnaces unless the sulfur has been removed from the oil. Measurements of SO_x emissions from a batch melter charged with batches having various sulfur contents showed a direct correlation between sulfur in the batch and SO_x emitted. The greater the sulfur content of the raw batch, the higher the SO_x emissions.

The amount of NO_x emitted from a glass-melting furnace depends upon several factors, some of which are not understood. One important factor is flame temperature: NO_x formations in the furnace increase as flame temperature increases. For example, during a recently completed

Table 5. AIR POLLUTANT EMISSIONS FROM VARIOUS PRODUCTION GLASS MELTERS

Investigators	CO	NO$_x$	Particulates, lb/hr	Halogens	SO$_x$
	ppm	ppm		ppm	ppm
IGT[2]	35 to 50[a]	490 to 700	6 to 8	1.0	28[e]
Ryder and McMackin[4]	0 to 5[b]	450 to 600	--	--	--
Stockham[5]	375[c]	340	--	7.1	267
Arrandale[1]	--	--	2 to 10[d]	--	--
Netzley[3]	--	--	2 to 10[d]	--	--

[a] 8% excess air.

[b] 25% to 45% excess air.

[c] Excess air unknown.

[d] Variable with production rate.

[e] Natural gas fired.

experimental program, NO_x emissions were measured during a complete firing cycle of a glass melter. NO_x emissions were highest at the beginning of the firing cycle and then, as the cycle continued, decreased by about 30%. At the beginning of the firing cycle, the combustion air is preheated to a higher temperature, which results in a hotter flame than at the end of the cycle when the checker-brick and hence the air have cooled considerably. Other major factors in NO_x formation in a glass melter, such as flame velocity and recirculation patterns of flue gases, are being studied.

Current Methods of Air Pollution Control

Methods of air pollution control currently in use in the glass industry are primarily electrostatic precipitation (ESP) and baghouses for particulates and the use of low-sulfur oil for SO_x emissions. In terms of equipment costs, ESP and baghouses are about the same upon installation. However, less energy is consumed by ESP. To be effective, baghouses require a substantial pressure differential, which creates a need for a substantial amount of horsepower to move the particulate-laden air through the baghouse. In addition, baghouses require more maintenance than ESP to be totally effective.

One of the problem areas faced by the glass industry in its attempts to clean up the emissions is the variances in regulations that exist from one state to the next. More than one company interviewed indicated that because of these variations, different solutions must be implemented to bring two plants, located in different states, but otherwise identical, into compliance. Thus, in one state, baghouse systems may adequately control a comapny's particulate emissions, while in a neighboring state, a process modification, the use of electric melters instead of fossil-fuel-fired melters, is necessary. Such variances are not only costly to a company, but they also may dramatically affect energy utilization, as in the above example.

Other emissions, such as carbon monoxide and hydrocarbons, can be controlled easily with proper combustion conditions. If opal or green glass is being produced, halogens such as chlorine and fluorine also are emitted in very large quantities from a fossil-fuel melter. However, the industry has converted completely to electric melting, and this switch has eliminated these emissions.

Trends in Process Modifications in the Glass Industry

According to the glass industry, several process modifications exist for potential implementation by the industry sometime in the future. These modifications would affect energy utilization and/or air pollution emissions and are as follows:

1. Expansion of process monitoring and control capacity
2. Electric melting
3. Electric boosting
4. Oxygen enrichment
5. Raw batch preheating
6. Raw batch agglomeration
7. Use of low temperature heat to drive compressors
8. Augmentation of heat transfer from flames
9. Submerged combustion.

Of these modifications, only the first three are considered by the industry to have potential for implementation in the near future. These three techniques are economically feasible and their technical feasibility has been demonstrated to the satisfaction of the industry, and implementation is already occurring. According to the glass industry, the latter modifications listed are generally considered to be economically unattractive or technically unfeasible in spite of published data to the contrary. The following discussion presents a brief description of the modifications involved and the industry's viewpoint concerning the implementation of each.

Expansion of Process Monitoring and Control Capacity

According to persons interviewed within the industry, there are several modifications that can be made in the area of process monitoring and control that will favorably influence the utilization of energy. One of these modifications is the use of improved temperature-sensing devices for continuous process monitoring. For example, infrared sensors focused on critical areas of the melter, such as the optical block on the bridgewall, are used to gauge melter performance. These sensors can be used not only to continuously monitor melter temperature, but their signals can be used to control fuel input, based on melter temperature. Another such modification is the use of flue-gas analyses to monitor excess air and maintain it at a minimum level. None of these monitoring techniques is expensive, and all of them would contribute to improving the efficiency of operation.

Electric Melting (and Boosting)

The glass industry strongly supports the implementation of electric melting and boosting primarily for reducing air pollutant emissions. Electric melting, as a method for producing glass, has proven to be technically and, in most cases, economically feasible by its relatively widespread use in the industry. (Actually, electric boosting, where a fuel-fired melter is supplemented by electric melting, is very popular and more prevalent within the industry than straight electric melting.)

Oxygen Enrichment

Oxygen enrichment is a technique whereby pure oxygen is added to the combustion air of a fuel-fired melter, resulting in an increase in flame temperature. This, in turn, results in a reduction in the fuel required to melt a ton of glass, or, alternatively, allows a melter operating at design capacity to boost its production above design capacity. Based on the results of the interviews with glass manufacturers, oxygen enrichment is a long-term goal, primarily because acceptance by the industry requires substantial changes in fuel and oxygen costs to economically justify implementation.

Raw-Batch Pretreatment

The area of raw-batch pretreatment includes batch agglomeration, or compaction, and preheating of the batch prior to charging into the furnace. Most of the companies interviewed feel that batch agglomeration is not economically justified within the near term for reasons of reduced energy utilization or reduced particulate emissions. However, at least one major glass manufacturer has recently put into operation several pelletizing lines to supply pelletized batch to the melters. There is no detailed data available on this operation at the present time.

Coupled with the compaction of glass batch is the idea of preheating the glass batch prior to charging it into the melter. It is clear that such a process must be coupled with a batch compaction process in order to minimize batch losses during preheating and to minimize particulate emissions from the batching operation. The industry contends that preheating of the batch will cause it to become sticky, making the charging operation next to impossible.

Submerged Combustion

Submerged combustion is a melting process whereby the fossil-fuel burner is located beneath the molten glass surface and the hot combustion products pass through the glass resulting in a very high rate of heat transfer from the gases to the glass. Because the product from this type of melter is foam glass — that is, it contains millions of air bubbles — it is unacceptable to the industry without substantial refining. The only possible use for submerged combustion would be in a premelter, which at least one company has implemented. However, because the refining step requires a substantial amount of energy (more than usual), it is not certain that there is a reduction in the overall amount of energy consumed to melt the glass. Consequently, substantial development is still required before it will become acceptable to the industry, thus making implementation long-term, at best.

Augmentation of Heat Transfer From Flames

This is a rather nebulous area for consideration. There are potentially many things that can be done to improve heat transfer from the flame to the molten glass. One approach is the use of devices that allow an operator to accurately and precisely position his burners. A second approach is the injection of water vapor into the flame, which theoretically increases the radioactive properties of the flame, resulting in an increase in the heat-transfer rate. The entire area of augmenting heat transfer has great potential, according to the industry, but implementation of most of the developments is deemed to be long-term.

Use of Low-Grade Thermal Energy

At least one company interviewed said that waste heat from the melting process, most of which is below 1000°F and consists of 20% of the energy that goes into melting the glass, could be used to directly drive turbines for air compressors, which would then be used in the blowing operations. Alternatively, but not as efficient, was the suggestion that this heat be used to drive turbines in the generation of electricity. While such practices are not currently used, with some development, usage might increase in the long-term.

Improvements in Equipment Design

Because of the rate at which equipment is replaced within the glass industry, implementation of improvements in equipment design are considered long-term. Improved energy utilization is expected from the application of better insulating techniques, improved regenerator design, and improved firing patterns by burner placement. Annealing-lehr efficiency is affected by numerous design considerations. Among the most prominent considerations are the use of light-weight lehr belts, the method of belt return, proper insulation of the heating zone, use of radiant burners in the heating coal sections, and design to prevent forward drift. Plant layout to minimize transit time of the glass between the forming machine and lehr is also important. As indicated, most of these design modifications are considered long-term, in terms of implementation and impact.

It is clear from the above discussion of process modifications that the glass industry feels that there is very little that can be done in the short-term to ease the energy shortage and air pollution emissions problems. With the exception of the installation of process monitoring equipment, the process modifications discussed are generally deemed to be long-term in implementation. Even in the area of process monitoring equipment, the opinion was expressed during the field interviews that the available equipment is not adequate to meet the demands of continuous operation in the climate of a typical glass plant.

Trends in Energy Utilization in the Glass Industry

In 1971, the latest year for which industry statistics covering energy utilization are available, a total of approximately 250 trillion Btu of energy was consumed by the glass industry. The breakdown according to the type of energy consumed was as follows: coal, 1.6%; fuel oil, 4.5%; natural gas, 88.7%; and electricity, 5.2%. Natural gas is the preferred fuel because it is clean burning and will not affect glass characteristics, such as color. Furthermore, the natural gas flame, when properly controlled, provides a longer furnace life than other fuels, primarily fuel oil.

Typically, fuel oil is a standby fuel for most major manufacturers. Conversion to oil firing is not an extensive undertaking, requiring only that burners be changed and certain control equipment modified. Nevertheless, investment costs for oil-fired furnaces are substantially higher than for natural gas. This is due in part to the requirement for a fuel oil storage facility and the requirement for equipment to heat the oil to reduce its viscosity and thus increase the efficiency of combustion. The industry is being forced to convert to fuel oil on the melters because of the curtailment of natural gas, particularly during the winter months. Some companies have experienced up to 100% curtailment of natural gas in some states. They believe that conversion to fuel oil on a large scale will occur in the near future.

Inevitably, the deciding factor in establishing fuel-use trends is cost. Currently, the cost of oil suitable for use in the melting operation is more than double the cost of a comparable amount of natural gas. In order to meet the requirements of glass quality and air pollutant emissions, the level of sulfur present in the oil must be less than 1%, adding substantially to the fuel price. Clearly, as the cost of natural gas continues to increase, the trend toward the use of fuel oil as the primary fuel (rather than a standby fuel) will increase.

As indicated above, 5.2% of the energy consumed by the glass industry is electricity. Electricity is consumed primarily in the melting process in the glass container industry. It is used as a production-boosting technique in conjunction with a fuel-fired melter or as the primary energy for melting. The amount of glass so produced is less than 500,000 tons per year. The majority of the electricity is used for mechanical drives, compressors, and similar applications. In the flat glass industry, where substantial amounts of power were required for grinding and polishing the glass, the conversion to the float glass process has shifted the use of electricity to a heating application — i.e., maintaining the tin bath in a molten state. Because electricity is such an expensive form of energy, it is not likely that it will replace the use of fossil fuels, as in electric melting. However, the use of electricity may increase in the flat glass industry as the use of the float process increases. Reluctance on the part of the companies interviewed to give out any energy-utilization figures on the float process is the cause for the uncertainty in establishing this trend.

Consideration of these factors leads to the conclusion that the trend in fuel utilization, according to the industry, is toward increased use of fuel oil as the primary fuel for melting. The consumption of electricity can be expected to increase in the annealing operations, particularly in the flat glass industry. Current projections for the availability of natural gas make its continued use by the industry unlikely in the long-term — if not impossible. Coal has never been an acceptable fuel to the industry and is not expected to assume any of the glass-manufacturing load.

Trends in Air Pollutant Emissions From Glass-Manufacturing Processes

According to representatives of the glass industry, the efforts of the industry to reduce air pollutant emissions are seve[illegible] hampered by the variations in regulations that exist from state to state. [illegible] lack of uniformity requires that different solutions to the problem be sought, depending on the location of the specific plant. This, in turn, adds substantially to the cost of pollution control. In addition, not only are the regulations variable from one location to another, but these regulations are constantly changing. As a result, very few air pollution control equipment installations have been made on glass furnaces, and there is very little data available in the effectiveness and cost of these devices. Estimates of energy cost for air pollution control range from 2% to 15% of the energy input to the industry. Clearly then, the effort to reduce emissions to within regulation through the installation of pollution control equipment is significantly hampered by all of the factors above.

Similarly, the industry is moving very slowly to implement process modifications to reduce emissions. The primary area is the modification of the batch formulation and batch pretreatment because the batch is the major source of pollutant emissions in the glass industry. Particulate emissions are the primary concern. No attention is being given to NO_x emissions at the present time. There are process modifications that should be considered for energy conservation, which will not necessarily result in an increase in NO_x emissions. Currently, NO_x emissions are not considered to be a problem, primarily because there are no regulations relative to the glass industry. Similarly, SO_x emissions, except as they contribute to the emission of particulates (as sodium sulfate), are not considered to be a serious problem. Since the primary source of these emissions is the fuel, the SO_x emissions will be a direct function of the amount of sulfur in the fuel. Otherwise, SO_x emissions will not be affected by process modifications.

Analysis

The data collected during this program indicate that the glass industry feels that only minor increases in energy-utilization efficiency can be made and that the only existing pollution problem is particulates, which are being controlled, but at a substantial economic and energy-utilization cost. Clearly, economic considerations are the primary factors in this evaluation. Some discrepancy appears to exist due to a lack of accurate and reliable information concerning the relevant areas, thus demonstrating the critical need for informing the industry in these areas.

In general, SO_x, NO_x, and particulates are the primary air pollutants from the glass manufacturing processes. Note that the concern is primarily with the melting process because this is the largest energy consumer and the major contributor to air pollutant emissions. However, the major pollution problem in the combustion process and efficient utilization of energy is NO_x emissions. The SO_x emissions which occur are due to the type of fuel used and they can be reduced merely by using low-sulfur fuels. SO_x emissions are not affected by the process modifications to reduce fuel consumption, other than the small reduction that would inherently occur by reducing fuel consumption. Particulate emissions cannot be viewed as arising in the combustion process because the primary fuels used in the industry, fuel oil and natural gas, do not produce particulates as effluents, as would coal, which is not used by the glass industry. The relationship between these emissions and energy utilization by the industry, can be seen by looking at the control method employed to determine the effect on energy consumption. (That is, how much energy is required to operate the control device?) It is not likely that operation of the control device will affect the energy utilization of any particular process. Process modifications to reduce energy consumption will not have any significant impact on these emissions. Care should be taken when analyzing process modifications and pollution control methods that consume electricity because it is necessary to look at the generating power plant to determine the true process energy consumption and air pollutant emission rates in the manufacturing plant. Thus, the only emission of concern in the glass industry is NO_x. While the formation of NO_x in the combustion process is not entirely understood, it is clear that the goals of reducing NO_x emissions and reducing energy consumption are seemingly at odds. NO_x formation is a temperature-related phenomenon; as temperature increases, NO_x emissions increase. On the other hand, increasing available heat to a process may result in increases in temperature, which in turn increase NO_x emissions. Analysis of the process modifications under consideration in the glass industry shows that there is a possibility of increasing NO_x emissions, but if the implementation is carried out properly, this need not occur.

By way of example, oxygen enrichment as a technique for boosting production rate and reducing fossil-fuel consumption has been proven to be very effective. The effectiveness is due to the increase in flame temperature that occurs as the percentage of oxygen in the combustion air increases and the percentage of nitrogen decreases. This increased temperature can then result in an increase in NO_x emissions. However, boosting the production rate, assuming no increase in fuel input, requires that this additional heat be taken from the flame and transferred to the glass. The net result is a flame at pre-oxygen enrichment temperature levels. If there is no need for the additional production, although uneconomical, the fuel input can be reduced to achieve the same net result.

Modification of the batching process, specifically, raw batch preheating and batch agglomeration, will have no impact on NO_x emissions on a per unit of energy basis. However, NO_x emissions are likely to be reduced due to an overall reduction of energy consumption. If, however, these modifications were coupled with the concept of submerged combustion, both fuel consumption and NO_x emissions per unit of energy consumed would decrease. Modification of the batching process would be required, particularly implementation of batch agglomeration, in order to prevent particulate emissions in the form of raw batch being carried out in the combustion products. The problem is that submerged combustion is not fully developed as a viable process because the product, foam glass, is unacceptable to the industry in that it fails to meet the quality standards for virtually any use.

Only brief mention has been made concerning the analysis of fuel consumption and air pollutant emissions relative to the use of electricity. Electric melting and boosting are believed to require less energy than straight fossil-fuel melters and are believed to virtually eliminate air pollutant emissions. These beliefs are based on operating data that show an all-electric melter to consume about 3 million Btu/ton of glass, compared with 6 million Btu/ton for a comparable fuel-fired melter producing the same type of glass. Operating data also indicate that because there are no combustion products, there are no NO_x, SO_x, or particulates given off. However, if the generating of that electricity is considered, the actual amount of energy consumed for melting is higher than for a straight fuel-fired melter. The data for air pollutant emissions are not clear but electric melting is not pollution-free.

If the industry heads in the direction that it is going for the short-term, that is, implementation of process monitoring and control devices, fuel consumption rates will decrease by 5% to 10% with no effect on pollutant emissions. For the long term, in spite of the great potential, it is not likely that major process modifications will be implemented by the industry. Consequently, the potential for reducing emissions and energy consumption is minimal.

As indicated above, the trend in fuel utilization is toward increased use of fuel oil and away from natural gas. In addition to the effects of this trend on particulates and SO_x emissions, there is likely to be a dramatic increase in NO_x emissions. Although there is only a small amount of data on NO_x emissions from glass-manufacturing processes, research on the formation of NO_x in combustion processes shows two major contributing factors to the formation — thermal factors in the furnace and the amount of nitrogen in the fuel. In the case of natural gas, where there is no fuel-bound nitrogen, NO_x emissions are due to thermal factors. But in the case of liquid or solid fuels, not only is NO_x produced by these same thermal factors, but additional NO_x is produced because of the presence of nitrogen in the fuel. Thus, an increase in the use of fuel oil by the glass industry will increase NO_x emissions.

Recommendations

As previously indicated, the overwhelming viewpoint of the glass industry is that only minimal reductions in energy consumption can be achieved. With respect to emissions, the industry feels that, considering the great variances in regulations from state to state, it is doing an adequate job. Thus, particulate emissions are seemingly well controlled with attempts to reduce SO_x emissions by using low-sulfur fuels. In the absence of an established standard, applicable to industry processes, the industry is not actively concerned with NO_x emissions. As a result, if most industry pollution control recommendations were implemented they would not help to reduce NO_x emissions. With this in mind, the recommendations that follow are intended to inform the industry. We are recommending, first, that programs be undertaken to determine what the true facts are in areas where data is limited. Specifically, there is only a minimal amount of data available on NO_x emissions from glass-manufacturing processes — most of it scattered and unreliable. Before any affirmative steps can be taken to deal with this problem, a base-line case must first be established.

Having established a base-line case, the next step is to support programs demonstrating and developing new technology that is applicable to the industry and that provides the greatest potential for solving the problems. Table 6 lists the program areas that should be considered. The order of listing is according to programs that afford the greatest potential for solving the problems in the shortest period of time. The table also presents estimates of improvements that may be obtained, where such estimates can reasonably be made. The programs in these recommended areas should be devoted to developing data, including operating and economic statistics. This data should then be used to convince the industry of the feasibility of these concepts, providing incentive for implementation. Clearly, in the case of submerged combustion, the programs required are more in the way of development. At its present state of development, submerged combustion is virtually unsuitable for use by the industry. But in light of the potential gains to be made, programs to further develop this concept are easily justifiable.

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Table 6. RECOMMENDED PROGRAMS FOR REDUCING EMISSIONS AND ENERGY CONSUMPTION IN THE GLASS INDUSTRY

Program	Expected Improvements in Energy Consumption, %	Expected Improvements in Air Pollutant Emissions
1. Develop current emission data	--	--
2. Raw batch pretreatment — i.e., preheating and agglomeration	25-50	25-50% potential NO_x reduction may reduce particulate in form of batch carry-over
3. Oxygen enrichment	5-15	No effect on NO_x, SO_x, or particulates
4. Augmentation of heat transfer from flames — e.g., burner positioning	10-20	Proportional NO_x reduction
5. Use of low-temperature heat for driving compressors	--	--
6. Development of submerged combustion process	50	Will substantially reduce NO_x emissions

Cement Industry

Summary

The cement industry includes all establishments engaged in the manufacture of hydraulic cement (generic term: portland cement), masonry, natural, and pozzolana cements. This study is limited to the production of portland cement because it accounts for 95% of the total cement manufactured in the United States, with the remaining 5% split among the other types.

Over the past 20 years, the cement industry has been growing at a steady annual rate of about 1.8%. According to industry estimates, this growth rate is expected to increase, ranging from 2.6% to 4.1% annually. It is reasonable to assume that actual production up to 1985 will fall within the range shown in Figure 5. Total U.S. cement production in 1973 is estimated at 81.8 million tons. It is expected to reach a minimum of 97 million tons in 1980 and 109 million tons in 1985.

The amount of energy consumed by the industry in 1973 is estimated to be 573 trillion Btu, based on average unit energy consumption of 7 million Btu/ton of cement produced. The primary sources of energy are natural gas, oil, coal, and electricity. Figure 6 illustrates energy consumption by type up to 1972, excluding electricity, and indicates that coal and natural gas are used more than fuel oil.

The industry is composed of 50 companies that operate 173 plants in the United States, including Puerto Rico. The annual practical production capacity, based on theoretical production capacity adjusted downward about 10% to reflect maintenance shutdowns, is in excess of 90 million tons of finished cement per year. The number of plants operated by an individual company may range from 1 to 14, and no single producer accounts for more than 7.3% of the total U.S. market.

Portland Cement Manufacturing Processes

Raw materials used in the manufacture of portland cement consist of limestone, chalk or marl, and seashells. These are combined with either clay, shale, slate, blast furnace slag, iron ore, or silica sand. The end product is a chemical combination of calcium, silicon, aluminum, iron, and other trace materials. The raw materials are first ground and blended together. Depending upon which of the two processes is used, water may be

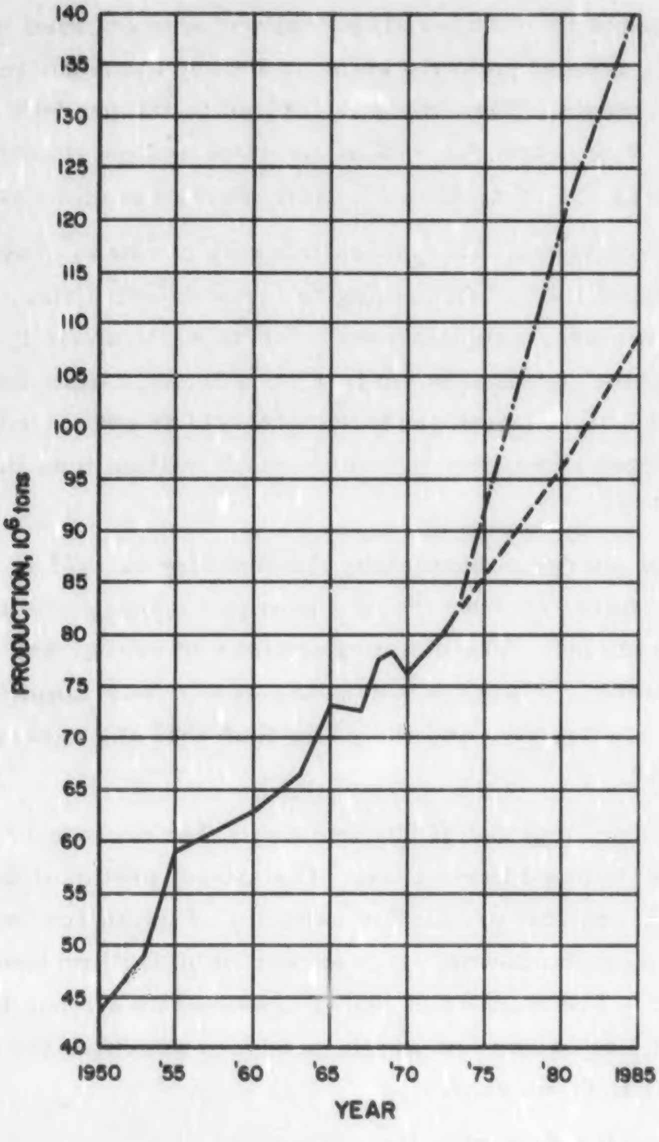

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Figure 5. ANNUAL CEMENT PRODUCTION WITH PROJECTION TO 1985

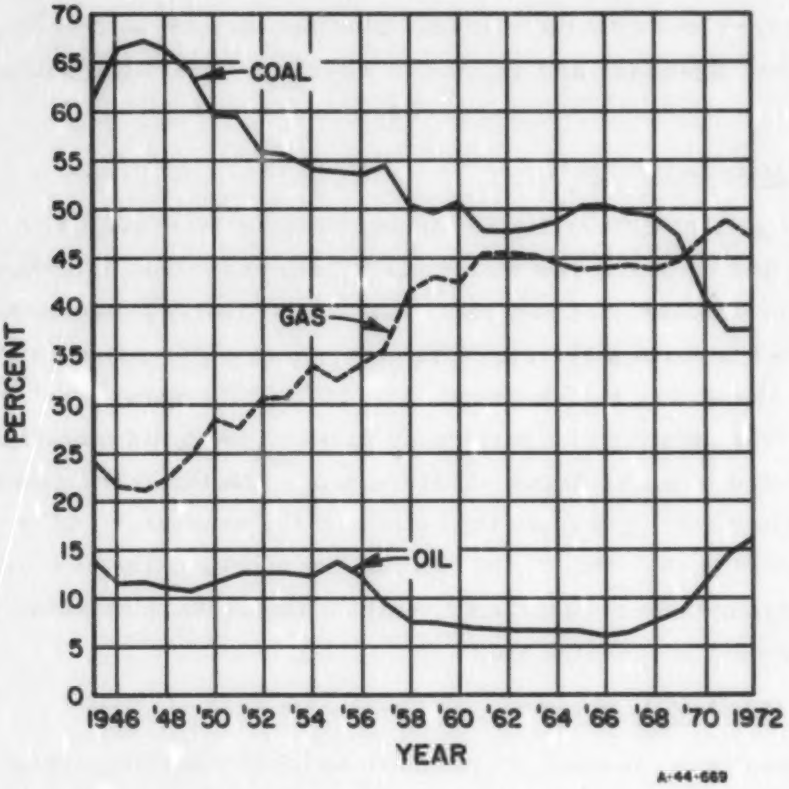


Figure 6. FUEL USAGE OF U.S. CEMENT INDUSTRY

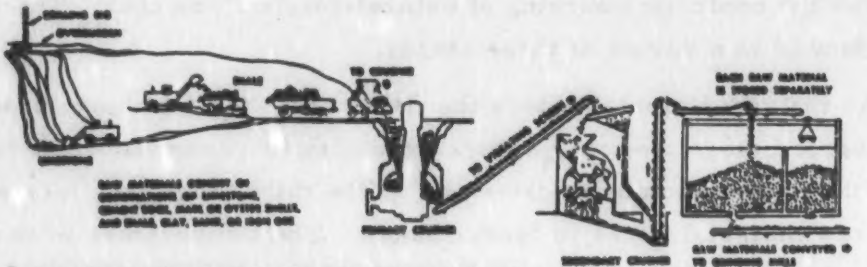
added during blending (the wet process) or the ingredients can be mixed on a dry basis (the dry process). In general, the moisture content of the raw materials determines the process used. If the moisture content is greater than 18%, by weight, the wet process will be used. If the moisture content is less than 18%, the dry process will be used. The next step is the calcining or burning of the mixed raw material in a rotary kiln (pronounced "kill"). During this step, the material is heated to approximately 2700°F (1500°C) and transformed into clinker, which has different chemical and physical properties than the raw materials had initially. The clinker is discharged from the kiln and cooled. The last step is the grinding of clinker to the desired fineness, and gypsum is added to control the setting time of the concrete.

Raw Material Preparation

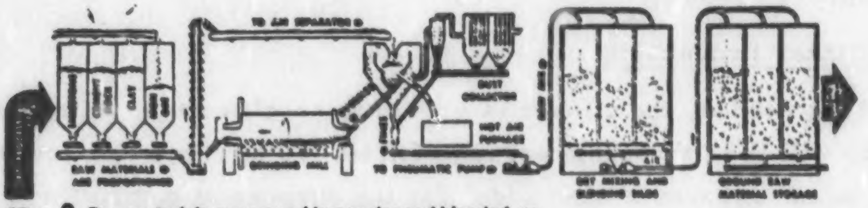
The step that differentiates the wet process from the dry process is the initial grinding of the raw materials. Both processes are shown in Figure 7. In the wet process, the raw materials are properly proportioned and combined with water to form a slurry. The slurry may be as much as 50% water. After mixing, the slurry is dewatered to a 20% to 30% water level in a continuous separator consisting of a large tank in which the solid material settles to the bottom, and water is drawn off at the top. The thickened slurry is then mechanically discharged from the bottom of the separator and is stored or is transferred to the rotary kiln. In the dry process, the raw materials are simply ground and proportioned, without the addition of water, and passed on to the next processing step.

Raw Material Burning

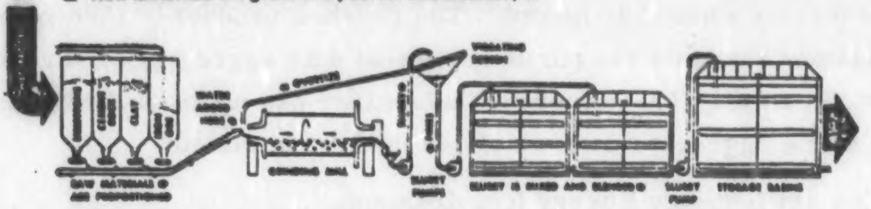
Burning is the heating operation in which the raw materials are burned to form a new product called clinker. The product is grayish-black in color, about marble size, and has different chemical and physical properties than the raw materials. The raw materials are charged continuously into a cylindrical rotary kiln, which turns at about 1 revolution per minute. The kiln varies in diameter — generally 12 to 14 feet. It is several hundred feet in length and lined with firebrick. Some kilns may be as large as 25 feet in diameter and 750 feet long. They are mounted at an angle slightly off horizontal, so that as they rotate, the raw material moves countercurrent to the flow of hot gases. The raw materials are charged into the high, charging


DRILLING RIG
OVERBURDEN
SHALE
TO CRUSHER
QUARRYING
RAW MATERIALS CONSIST OF COMBINATIONS OF LIMESTONE, CEMENT ROCK, MARL OR OYSTER SHELLS, AND SHALE, CLAY, SAND, OR IRON ORE
PRIMARY CRUSHER
TO VIBRATING SCREENS
EACH RAW MATERIAL IS STORED SEPARATELY
SECONDARY CRUSHER
RAW MATERIALS CONVEYED TO GRINDING MILLS

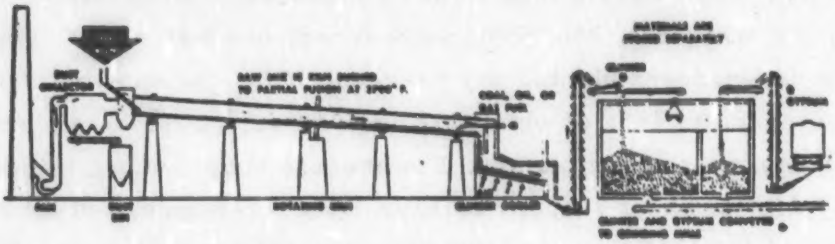
1 Stone is first reduced to 5-in. size, then ¾-in., and stored.


TO AIR SEPARATOR
DUST COLLECTOR
HOT AIR FURNACE
GRINDING MILL
TO PNEUMATIC PUMP
RAW MATERIALS ARE PROPORTIONED
DRY MIXING AND BLENDING SILOS
GROUND RAW MATERIAL STORAGE
OR

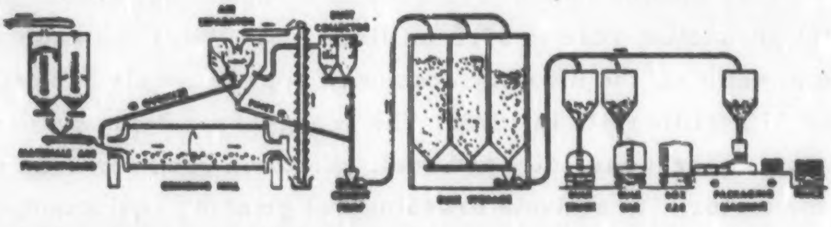
2 Raw materials are ground to powder and blended, or


VIBRATING SCREEN
WATER ADDED HERE
GRINDING MILL
SLURRY PUMPS
RAW MATERIALS ARE PROPORTIONED
SLURRY IS MIXED AND BLENDED
SLURRY PUMP
STORAGE BASINS

2 Raw materials are ground, mixed with water to form slurry, and blended.


DUST COLLECTOR
RAW MIX IS KILN BURNED TO PARTIAL FUSION AT 2700° F.
COAL, OIL, OR GAS FUEL
MATERIALS ARE STORED SEPARATELY
CLINKER
GYPSUM
FAN
DUST BIN
ROTATING KILN
CLINKER COOLER
CLINKER AND GYPSUM CONVEYED TO GRINDING MILLS

3 Burning changes raw mix chemically into cement clinker.


AIR SEPARATOR
DUST COLLECTOR
MATERIALS ARE PROPORTIONED
GRINDING MILL
CEMENT PUMP
BULK STORAGE
BULK TRUCK
BULK CAR
BOX CAR
PACKAGING MACHINE
TRUCK

4 Clinker with gypsum is ground into portland cement and shipped.

Source: Portland Cement Association.

Figure 7. STEPS IN THE MANUFACTURE OF PORTLAND CEMENT

end to the low, discharging end. A hot flame is produced at the discharge end by the controlled burning of natural gas, oil, or coal. The raw materials are heated in a series of three stages.

As the raw material enters the first stage, the moisture is driven off. In the second stage the temperature gradually increases to about 1800°F (980°C), and the carbon dioxide is driven off. The third stage, the hottest, is where the raw material burns to form clinker. The temperature of the third stage is about 2700°F (1500°C). The resulting clinker is cooled upon discharge and stored until needed.

Clinker Processing

When needed, the clinker is ground to specification, a fine powder 90% of which will pass through a screen with 40,000 openings per square inch. At this point, gypsum is also added for the purpose of controlling setting time of the concrete when it is mixed. The finished product is then sold to concrete companies that mix the portland cement with aggregate of various types to form concrete. The cement manufacturer has no control over the composition of the aggregate with which the cement is mixed.

Cement Industry Energy Requirements

In 1972, there were a total of 454 cement kilns in operation in the United States. Of this total, 250 (55%) were in wet-process plants, and 204 (45%) were in dry-process plants. By year-end 1973, the number of kilns in operation decreased to 445, of which 247 were in wet-processing plants and 198 were in dry-processing plants. The average annual capacity per kiln, both wet and dry, is about 194,000 tons/yr. The average age of all kilns is 25 years, and 110 (24%) are at least 40 years old.

In 1972, 79 million tons of cement was domestically produced, and in 1973, domestic production rose to 81.8 million tons. Using the estimate of 7 million Btu/ton of cement, the industry consumed approximately 553 trillion Btu in 1972 and 573 trillion Btu in 1973. The energy consumed was in the form of electricity, natural gas, oil, and coal. Electric power is used in all cement plants for motors, to activate crushing and grinding equipment, for pollution control equipment, and for general lighting. Fossil fuels, coal, oil, and natural gas are used directly in the rotary kiln to transform the raw materials into clinker. The information given in Table 7, as provided by the Portland

Table 7. U.S. CEMENT INDUSTRY KILN FUEL USAGE (1973)

Type of fuel	No. of plants*	Percent of capacity
Coal	52	30
Oil	13	8
Natural gas	26	10
Coal, oil	7	5
Coal, natural gas	32	17
Oil, natural gas	38	26
Coal, oil, natural gas	5	4
Totals	173	100%

Source: Portland Cement Association, Market and Economic Research Department.

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*Number of plants includes all clinker-producing units, with white and gray plants at same site counted as two plants. Grinding-only plants are not included.

Cement Association, shows the breakdown of fuel consumption on the basis of plant distribution and kiln fuel use in 1973.

The energy consumption of the various stages of cement processing is shown in Table 8.

Table 8. ENERGY CONSUMPTION IN CEMENT PROCESSING

Process/ Fuel Type	Quarry	Crushing, Milling, Mixing	Burning	Finish Milling, Packing	Total
	1000 Btu/ton of cement				
Wet:					
Electrical	8.2	113.5	85.9	212.8	420.4
Fuel	16.0	--	5560.0	--	5576.0
	24.2	113.5	5645.9	212.8	5996.4
Dry:					
Electrical	5.8	154.4	94.5	228.6	483.3
Fuel	16.0	600.0	4600.0	--	5216.0
	21.8	754.4	4694.5	228.6	5699.3

Electricity is the major form of energy consumed in the initial steps of cement manufacturing — quarrying, crushing, milling, and mixing — providing mechanical energy to operate the crushers, grinders, and blenders. Prior to the development of ball-and-tube mills, the dry process required more electrical energy than the wet process because the power requirements were greater for crushing and grinding the harder raw materials. The fuel requirements for the dry process are greater than for the wet process because the raw materials must be dried to remove all the moisture content, which can be as high as 18%. The amount of fuel used for drying is about 600,000 Btu/ton of cement produced. The amount of electricity consumed for the wet process is about 121.7 Btu/ton of cement and about 160.2 Btu/ton of cement for the dry process. If electrical generating is considered (assuming generating efficiency of 33-1/3%), the Btu consumption is equivalent to 365.1 and 480.6, respectively, per ton of cement produced. The additional requirements for the dry process are attributable to increased horsepower for fans and dust control equipment.

Although the average energy consumption for the burning process is about 6.4 million Btu/ton of cement, actual consumption can range from 3.7 to 9.0 million Btu/ton. The information given in Table 8 is for newer, well-maintained plants (less than 25 years old); the average energy consumed in the wet process is 5.6 million Btu/ton and 4.7 million Btu/ton in the dry process. The amount of energy consumed is determined by many factors, such as chemical and mineral composition of the raw materials, particle-size distribution and fineness of the charge, length pitch and speed of kiln rotation, and the efficiency of combustion and heat-recovery systems.

The most pronounced difference between the wet and dry processes is in the burning stage. As shown in Table 8, the difference between the wet and dry processes is 951,400 Btu/ton of cement. The wet process requires about 20% more energy for burning than the dry process because of the need to vaporize the additional water.

As shown in Table 8, approximately 212,800 Btu of energy is consumed in the final stage of the wet process and 228,000 Btu in the dry process.

Although no revolutionary changes have occurred in the manufacture of portland cement in the last 60 years, improved efficiency and reduced fuel consumption have been brought about on an evolutionary basis. The U.S. industry, however, had not been taking advantage of these changes until the last year or two. The remainder of the world's cement producers have been converting from the wet process to the dry process, which consumes less energy per unit of production.

The primary reason for this is that fuel has been cheap in the United States, as compared with the cost of fuel in other countries. The trend toward dry processing is beginning to occur in the United States, brought about by increased fuel shortages, particularly natural gas and oil. At the present time, approximately 45% of the fossil fuel energy consumed by the cement industry is natural gas, 40% coal, and 15% oil.

Air Pollutant Emissions From Cement-Manufacturing Processes

The major air pollutant emission problem in the manufacture of portland cement is particulates, which occur in all phases of cement manufacturing from crushing and raw material storage to clinker production, clinker grinding, storage, and packaging. However, emissions also include the products of combustion of the fuel used in the rotary kilns and drying operations; these emissions are typically NO_x and small amounts of SO_x. Table 9 summarizes the emissions from cement-manufacturing processes without controls.

The largest source of emissions in cement plants is the kiln operation. At present, about 56% of the cement kilns in operation use the wet process, and 44% use the dry process. Based on this information, estimates of total emissions from cement plants in 1972 are given in Table 10. These estimates, because of a lack of data, assume the use of no controls by the industry, and without an inventory of equipment in use, they cannot be refined.

Most efforts to control air pollutant emissions focus on particulates because they are not only the greatest problem, but also the easiest to control. The most desirable method of control is to collect the dust and recycle it by injecting it into the burning zone of the kiln, thus converting it to clinker. However, because of the high alkali content of the dust and its potentially bad effects on product quality, only a limited amount of dust can be recycled.

Because of the complications of kiln burning and the large volumes of gases and materials that are handled, several dust collection systems have been developed. Depending upon the temperature of the effluents and the emission standards of the community, the industry uses mechanical collectors, electrical precipitators, baghouse filters, or combinations of these devices to control emissions. Typically, in treating the flue gases from the kiln operation, mechanical separators are normally required ahead of either

Table 9. EMISSION FACTORS FOR CEMENT MANUFACTURING WITHOUT CONTROLS[a, b]

Pollutant	Dry Process		Wet process	
	Kilns	Dryers, grinders, etc.	Kilns	Dryers, grinders, etc.
Particulate[c]				
lb/ton	245.0	96.0	228.0	32.0
kg/MT	122.0	48.0	114.0	16.0
Sulfur dioxide[d]				
Mineral source[e]				
lb/ton	10.2	–	10.2	–
kg/MT	5.1	–	5.1	–
Gas combustion				
lb/ton	Neg[f]	–	Neg	–
kg/MT	Neg	–	Neg	–
Oil combustion				
lb/ton	4.2S[g]	–	4.2S	–
kg/MT	2.1S	–	2.1S	–
Coal combustion				
lb/ton	6.8S	–	6.8S	–
kg/MT	3.4S	–	3.4S	–
Nitrogen oxides				
lb/ton	2.6	–	2.6	–
kg/MT	1.3	–	1.3	–

[a] One barrel of cement weighs 376 pounds (171 kg).

[b] These emission factors include emissions from fuel combustion, which should not be calculated separately.

[c] Typical collection efficiencies for kilns, dryers, grinders, etc., are: multicyclones, 80 percent; electrostatic precipitators, 95 percent; electrostatic precipitators with multicyclones, 97.5 percent; and fabric filter units, 99.8 percent.

[d] The sulfur dioxide factors presented take into account the reactions with the alkaline dusts when no baghouses are used. With baghouses, approximately 50 percent more SO_2 is removed because of reactions with the alkaline particulate filter cake. Also note that the total SO_2 from the kiln is determined by summing emission contributions from the mineral source and the appropriate fuel.

[e] These emissions are the result of sulfur being present in the raw materials and are thus dependent upon source of the raw materials used. The 10.2 lb/ton (5.1 kg/MT) factors account for part of the available sulfur remaining behind in the product because of its alkaline nature and affinity for SO_2.

[f] Negligible.

[g] S is the percent sulfur in fuel.

Table 10. ESTIMATED TOTAL EMISSIONS FROM CEMENT PLANTS IN 1972

	Dry Process		Wet Process		
Pollutant	Kilns	Dryers, etc.	Kilns	Dryers, etc.	Total
Particulates, tons	4.5×10^{6}	1.8×10^{6}	5.3×10^{6}	0.7×10^{6}	12.3×10^{6}
Sulfur Dioxide, tons*	0.19×10^{6}	--	0.24×10^{6}	--	0.43×10^{6}
Nitrogen Oxides, tons	0.047×10^{6}	--	0.060×10^{6}	--	0.107×10^{6}

* Does not include emissions due to sulfur in fuel because these numbers depend on the sulfur content of the fuel, which is variable.

precipitators or glass bag collectors. However, wet-process kilns, which have lower exit-gas temperatures than dry-process kilns and relatively high moisture in the exit gases, are commonly followed directly by the precipitators because the moisture contributes to more satisfactory precipitator operation.

Efficiency of particulate removal depends upon the types and combinations of equipment used. Typically, multicyclone filters have an efficiency of 80%, and electrostatic precipitators have an efficiency of 95%. A combination of electrostatic precipitators and cyclones has an efficiency of 97.5%. Fabric filters (baghouses and the like) operate at a 99.5% removal efficiency. From this information, adequate equipment for particulate control apparently is readily available.

SO_x emissions result from burning the raw meal in the kiln. There are two sources of emissions in the kiln: sulfur in the raw material and sulfur in the fuel. The amount of sulfur present varies from plant to plant and with geographic location. Most of the sulfur dioxide emissions are inherently controlled in the process of cement manufacturing because about 75% of the raw feed is converted to calcium oxide, which reacts with sulfur dioxide. In addition, the presence of sodium and potassium compounds in the raw material aids in the direct absorption of sulfur dioxide into the product. However, the variable chemistry and operating conditions in U.S. cement plants affect the amount of sulfur dioxide entrapment and, in some cases, the quality of the product. Sulfur dioxide entrapment of this type seems to be about 75% in those plants for which data are available. Sulfur dioxide also is removed by this same mechanism in baghouse filters, in which the sulfur-dioxide-laden gases contact the collected cement dust. The degree of control by sulfur dioxide absorption depends upon the alkali and sulfur content of the raw materials and fuel.

Trends in Industrial Process Modifications as Estimated by Industry

Several developments involving the modification of the equipment used in the manufacture of portland cement have improved energy utilization. Almost all of these developments are centered around the rotary kiln and the burning process. To reduce the amount of energy consumed in this process, the heat-transfer rate from the combustion gases to the charge must be increased. The modifications can be classified into near-term, 1 to 5 years, and long-term, 5 to 10 years, as far as implementation is concerned. Near-term modifications consist of:

- Chain systems
- Enlargement of kiln feed end
- Oxygen enrichment
- Waste-heat recovery

Chain Systems

Chain systems can be utilized in both wet and dry process kilns. Chains are installed at the feed end of the kiln for the purpose of absorbing heat from the gas stream and transferring it to the raw material mix as the kiln revolves. As the kiln rotates, the chains emerge from the raw material mixture, thus providing a larger surface-area contact with the hot gases. Estimates of fuel savings derived from the implementation of chain systems are shown below in Table 11, and in Figure 8.

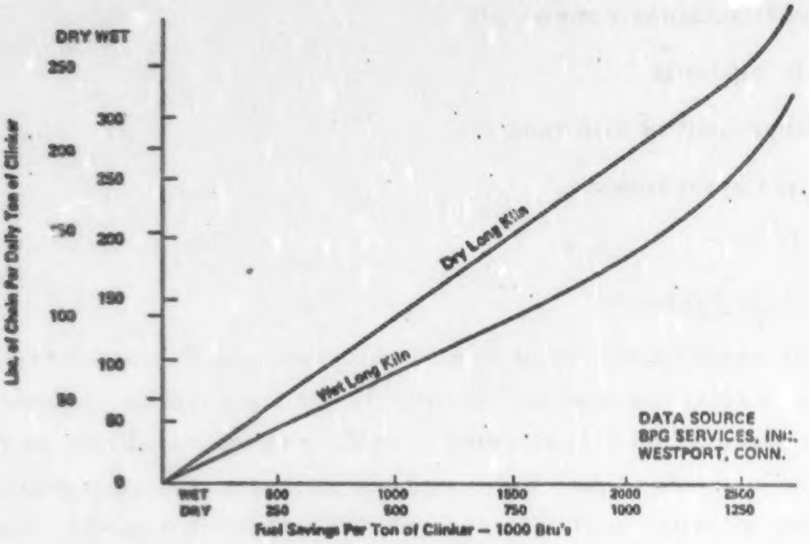
Table 11. FUEL SAVINGS FOR KILNS WITH CHAIN SYSTEM COMPARED TO KILNS WITHOUT CHAIN SYSTEM

Lb of chain per daily ton of clinker		Fuel savings—Btu per ton of clinker	
		Wet	Long dry
100		1,150,000	500.000
200		2.100.000	1,000,000
100	Difference	950,000	500,000

In order to achieve the maximum benefit of a chain system it must be carefully maintained. The effectiveness of the installation is reduced in direct proportion to the amount of reduction in chain surface area. For example, a reduction in chain weight equivalent to 25% will reduce the heat absorbing capability by 25%. Chain systems are designed for a specific kiln, taking into consideration structural design along with material and temperature profiles.

Enlargement of Kiln Feed End

Seventy-five percent of the existing rotary cement kilns in the United States are of a single diameter. Enlargement of the kiln feed end can increase thermal efficiency and production capacity. Thermal efficiency is increased by



DATA SOURCE
BPG SERVICES, INC.
WESTPORT, CONN.

Figure 8. THERMAL EFFICIENCY FOR CHAIN SYSTEMS IN LONG WET AND DRY KILNS

distributing the radiation heat loss over a greater quantity of material produced, thus resulting in reduced unit radiation losses.

The enlargement of the kiln feed end allows a larger quantity of chain to be installed, which can further increase kiln efficiency. This is especially applicable to dry-processing plants since most of the wet-processing plants have a sufficient amount of chain to reduce exit gas temperatures to 400°F, the practical, lower limit. In one instance, a cement manufacturer was able to increase production rates by almost 30% by increasing the kiln feed end diameter from 12 to 14.5 ft. Fuel consumption was reduced by about 20%. The quantity of fuel consumed in the kiln declined from 4.8 million Btu/ton to 3.9 million Btu/ton. The modification was accomplished during the course of a 1-month shutdown for each kiln involved. The primary factors to be considered prior to such a modification include capacity, available horsepower, and existing foundations.

Oxygen Enrichment

Much work has been done to determine the feasibility of enriching the combustion air of a rotary kiln with oxygen to increase production and reduce fuel consumption. One such program used oxygen lancing, a technique in which oxygen is introduced directly into the combustion chamber, rather than being introduced into the combustion air fan and mixed with the air. The production rate of the kiln increased 40%, and the fuel consumption decreased by 15% per ton of product. Another program used oxy-fuel burners and achieved comparable results. In spite of its technical success, oxygen enrichment is not commonly used in U. S. cement plants. The primary deterrent is that the high cost of oxygen cannot presently be justified by the improvements in efficiency. However, if similar results could be achieved at lower oxygen consumption rates, or if fuel availability to this industry becomes severely restricted, the process may be given more consideration.

Waste-Heat Recovery

Two methods are employed in the recovery of waste heat from cement kilns. These are waste-heat boilers and raw material drying. The use of waste-heat boilers is generally declining because of the low efficiency of making steam at the far end of a kiln. To a certain extent, chain systems have been installed in place of steam generation from waste heat and are more efficient.

Waste heat can be used to dry the raw materials prior to entry into the kiln. The moisture content can be reduced from 7% to 8% levels to approximately 0.5%. The amount of fuel saved is about 500,000 Btu/ton of cement produced. The drying of raw materials with waste heat can be accomplished in rotary dryers, roller mills, or air suspension preheater units. This is discussed as part of the long-term equipment modification section.

One major problem area exists in the utilization of waste heat to dry raw materials. The temperature of the exit gas from the dryer is in the range of 220° to 250°F. The temperature is below the dew point of sulfuric acid and is relatively close to the water dew point. Therefore, careful design and stringent maintenance practices are required to preclude corrosion or condensation in the duct work and pollution-abatement devices.

Long-term equipment modifications consist of the following:

- Installation of preheaters

- Conversion to dry process.
- Use of vertical kiln.

Preheater Installation

A major advance in reducing energy consumption in the burning process of cement is the separation of the first stage from the kiln and preheating the raw material up to near required temperatures before it enters the kiln. The methods in which this can be accomplished are summarized below in Table 12, which shows the effect of each method on energy consumption by using current practice.

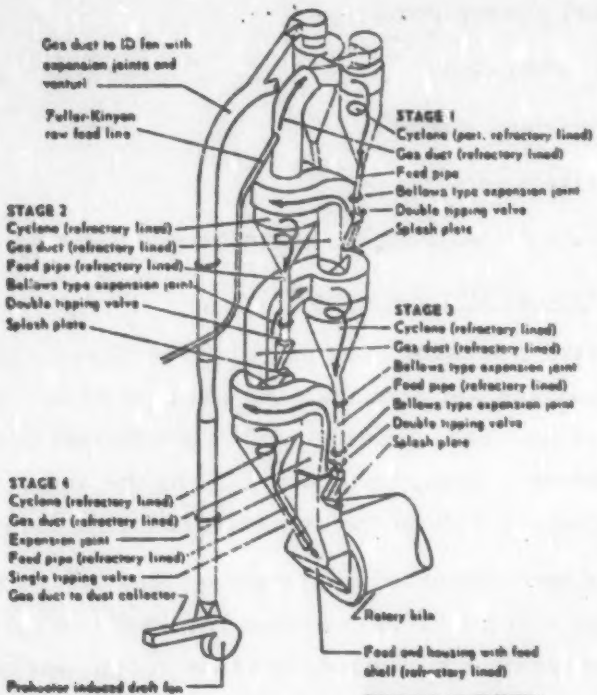
Table 12. ENERGY CONSUMPTION OF VARIOUS CEMENT-MANUFACTURING PROCESSES

Process	Energy Consumption, 10^6 Btu/ton	Reduction Over Average Current Practice, %
Wet		
Long Kiln	5.94	--
Calcinator and Short Kiln	4.68	26.9
Semiwet		
Preheater and Short Kiln	3.60	43.8
Dry		
Long Kiln	4.68	--
Suspension Preheater and Short Kiln	3.15	50.8
Semidry		
Grate Preheater and Short Kiln	3.42*	46.6
Vertical Kiln	4.14*	35.3

* Includes 0.54 million Btu/ton for drying.

The operation of the preheater shown in Figure 9 involves four parallel flow cyclone heat exchangers. Each cyclone includes a long riser where raw feed is introduced and conveyed upward into the cyclone in parallel flow with the hot gas from the preceding cyclone. This system provides intimate contact between raw material feed particles and the hot gases, resulting in a rapid rate of heat exchange.

Eacy cyclone spins out the feed where the next lower cyclone receives it by gravity discharge and the gases get successively hotter. The process through the four cyclones increases the temperature of raw material feed from about 160° at the point of entry to 1450°F just before entering the kiln. The system achieves apparent calcination of about 45% prior to entry into the kiln.


Gas duct to ID fan with expansion joints and venturi
Fuller-Kinyon raw feed line
STAGE 1
Cyclone (part. refractory lined)
Gas duct (refractory lined)
Feed pipe
Bellows type expansion joint
Double tipping valve
Splash plate
STAGE 2
Cyclone (refractory lined)
Gas duct (refractory lined)
Feed pipe (refractory lined)
Bellows type expansion joint
Double tipping valve
Splash plate
STAGE 3
Cyclone (refractory lined)
Gas duct (refractory lined)
Bellows type expansion joint
Feed pipe (refractory lined)
Bellows type expansion joint
Double tipping valve
Splash plate
STAGE 4
Cyclone (refractory lined)
Gas duct (refractory lined)
Expansion joint
Feed pipe (refractory lined)
Single tipping valve
Gas duct to dust collector
Rotary kiln
Feed end housing with feed shelf (refractory lined)
Preheater induced draft fan

DATA SOURCE: FULLER COMPANY

Figure 9. AIR-SUSPENSION PREHEATER KILN

Acceptance of the preheater by the U.S. cement industry has not been favorable. About one-half of the 13 systems installed since the unit has been developed are currently shut down. This has been attributed to inadequate knowledge regarding the process and the effects of alkalies, chlorides, and combustibles found in the raw materials on the operation of the system.

Another system has been developed that is a modification of the suspension preheater and can overcome the effects of the alkalies and combustible problems. The unit is referred to as the secondary furnace (SF) system and is basically the same as the suspension preheater with the addition of a separate combustion chamber at the base of the unit. The system increases the calcination rate from the aforementioned 45% for the suspension preheater to approximately 90% prior to entry into the rotary kiln. The SF system was developed in Japan and Germany, and the anticipated benefits, based on results of units operating in Japan, include –

- Increased kiln capacity
- Reduced firebrick consumption per ton of clinker produced
- Reduced fuel consumption
- Lower NO_x emissions
- Improved process control
- Improved alkali control
- Lower installed cost than the suspension preheater.

Conversion to Dry Process

As previously discussed, the dry process of cement manufacture requires less energy than the wet process. As the cost of fuel continues to increase, it becomes a larger part of the overall manufacturing cost, and greater attention will be directed toward reducing it. At the end of 1973, wet-process plants accounted for 58% of the cement-producing capacity in the United States.

The cost of converting existing wet-process kilns to the dry process is estimated to be about $41/ton of capacity. This is regarded by the industry as a nearly impossible task because of its recent period of depressed earnings, making it difficult to attract new capital.

Vertical Kilns

The vertical kiln is not a new concept in cement technology, but when it was first introduced about 75 years ago, its performance was unsatisfactory. It was unable to produce cement of consistently good quality; fluctuations in strength, setting, and soundness properties of the cement were very high. However, the vertical kiln has seemingly been developed so that these problems have been solved. Satisfactory performance of the vertical kiln requires that the raw materials be dampened and nodulized prior to being fed into the kiln. It also requires the use of low-volatile fuels, such as coal. In the vertical kiln, the nodules and fuel are fed continuously into the top of the kiln, and the clinker is extracted, cold, from the bottom by a rotating grate. Fuel consumption in a vertical kiln is about 3.6 million Btu/ton of clinker — more than 40% less than the average fuel consumption of rotary kilns (6.4 million Btu/ton). Further development is expected to reduce this figure to 2.6 million Btu/ton.

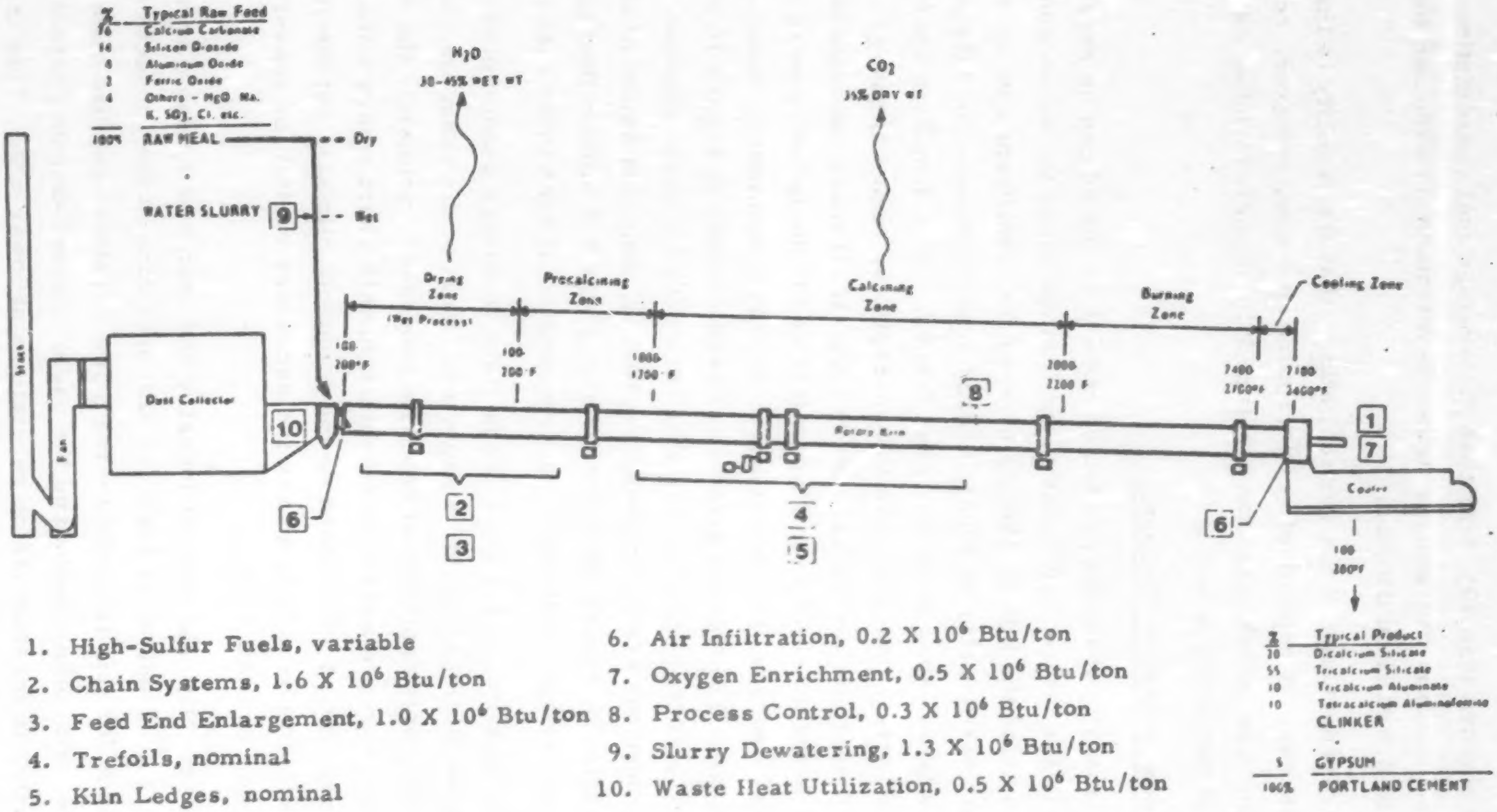
One disadvantage of the vertical kiln is that its capacity is limited to about 300 tons/day. A number of vertical kilns in a row, however, require less space and cost much less than a rotary kiln of corresponding capacity, so output is not really a problem.

Trends in Energy Utilization

The energy consumed per ton of cement produced can be expected to decrease in the future, and most of the methods used to reduce consumption will center around the kiln as the major area for significant energy savings. In the short term (prior to 1985), energy consumption by the kiln process can reasonably be expected to decrease from 7.0 to 4.7 million Btu/ton in all kilns. Figure 10 summarizes the concepts for reducing energy consumption in the short term on the typical rotary kiln. If all these concepts were implemented to the maximum extent possible and if the industry were to switch over to the dry process, the reductions in energy consumption stated above would be realized. The figures given after each concept in Figure 10 are the reductions in energy consumption that have actually been achieved. However, these reductions are not cumulative; that is, implementation of all these concepts would not reduce energy consumption by 5.4 million Btu/ton — the summation of savings realized by implementation of each individual concept.

In the long run, after 1985, reductions in energy consumption to below 3.5 million Btu/ton should be expected. Most of the reductions will be a result of the implementation of new kiln processes, primarily the vertical kiln and suspension preheaters in combination with short rotary kilns. The rate of implementation will depend on the economic climate, but the industry is not expected to be able to amass the necessary capital for converting to these new processes until 1985.

Until recently, the cement industry had been undergoing a trend away from the use of coal and oil as fuels for kiln operation in the production of clinker. The reason for this is twofold — the price of natural gas had been inexpensive compared with other fuels, and the use of cleaner-burning natural gas enabled the industry to meet emission regulations at lower cost. This trend, however,


%
Typical Raw Feed
76 Calcium Carbonate
14 Silicon Dioxide
6 Aluminum Oxide
3 Ferric Oxide
4 Others - MgO, Na, K, SO3, Cl, etc.
100% RAW MEAL
Dry
WATER SLURRY
9
Wet
Stack
Fan
Dust Collector
10
6
H2O
30-45% WET WT
Drying Zone
(Wet Process)
100-200°F
Precalcining Zone
100-200°F
1000-1700°F
CO2
35% DRY WT
Calcining Zone
Rotary Kiln
8
2000-2200°F
Burning Zone
2400-2700°F
2100-2400°F
Cooling Zone
1
7
Cooler
6
2
3
4
5
100-300°F
%
Typical Product
20 Dicalcium Silicate
55 Tricalcium Silicate
10 Tricalcium Aluminate
10 Tetracalcium Aluminoferrite
CLINKER
5 GYPSUM
100% PORTLAND CEMENT

1. High-Sulfur Fuels, variable
2. Chain Systems, 1.6 X 10^6 Btu/ton
3. Feed End Enlargement, 1.0 X 10^6 Btu/ton
4. Trefoils, nominal
5. Kiln Ledges, nominal
6. Air Infiltration, 0.2 X 10^6 Btu/ton
7. Oxygen Enrichment, 0.5 X 10^6 Btu/ton
8. Process Control, 0.3 X 10^6 Btu/ton
9. Slurry Dewatering, 1.3 X 10^6 Btu/ton
10. Waste Heat Utilization, 0.5 X 10^6 Btu/ton

Figure 10. SHORT-TERM ENERGY-SAVING CONCEPTS IN THE U.S. CEMENT INDUSTRY

is reversing itself because of the scarcity and rising costs of energy, particularly natural gas.

Results of field interviews indicate the industry is well aware of the changes taking place in terms of energy availability and price. In light of current energy shortfalls and price increases, the industry can pursue one or a combination of three courses of action. These are the conversion from natural gas and oil to coal, which is more readily available; increased research and development work directed toward improving the technology of manufacturing cement; and implementation of the more fuel-efficient technologies that are available.

The conversion of cement plants from natural gas and oil to coal is the most practicable measure the industry can undertake in the short-term in order to alleviate energy-supply problems. This appears to offer only a partial solution to the problem because many plants are not located close enough to coal fields to make conversion economically feasible. Transportation costs of the coal could override any benefit gained from such a conversion. In addition, some plants are located in regions where coal could become available if new mines were opened. This places dependence upon the coal industry to make the new supplies available through additional capital investment. Until the investment can be made and the necessary lead times met, a short-supply situation could occur in the near term. In addition, some of the plants currently using natural gas do not have adequate space available for stockpiling the quantity of coal necessary to maintain production on an uninterrupted basis between coal shipments.

In some areas of the country, the use of coal has been precluded by environmental restrictions that limit the sulfur content of fuels used. This is an additional factor that can restrict the conversion of equipment to coal.

The second course of action is to accelerate research in the area of improving cement-manufacturing technology, Such activity would include basic research into new methods of cement manufacture, with emphasis placed on improving the efficiency of energy utilization. Research funds required would amount to approximately $18.5 million — about 1% of industry sales. This is several times current industry funding levels in research programs.

The implementation of more energy-efficient technologies is the third option available in the near term. If energy efficiency is the only criteria selected for process evaluation and selection, that is, wet or dry, the dry process is more efficient. Three important factors deter widespread conversion to the dry manufacturing process within the near-term time frame. Two of the factors are equipment availability and the long lead time for conversion of about 2 years. The third factor, and probably most important, is the availability of capital for such a conversion. According to industry estimates, the cost of such a conversion would be $41/ton of capacity, or a total of $2.03 billion to convert all existing wet plants.

Information obtained during the course of interviews with cement manufacturers was related to current energy availability and cost. Natural gas is available on an interrupted basis only and, if available, is still subject to curtailments that have been in the range of 10% of a base year. The base year is 1972. The availability of natural gas is subject to many regional variations and is dependent upon whether or not the gas is purchased from intrastate or interstate suppliers. Generally, availability has been good from intrastate sources.

The cost of intrastate natural gas is much higher than interstate natural gas because of the absence of Federal regulation. In one instance, the cost of interstate natural gas had increased about 43% from 35¢/1000 CF in 1972 to 50¢/1000 CF at year-end 1974. In some regions of the country, the intrastate cost of natural gas was reported to be as high as 90¢/1000 CF. As a result, the cost of natural gas fuel has become a larger portion of the cost of cement manufacture and interest in alternative sources of energy has been created.

Coal supplies have not been adversely affected as has natural gas. However, the price of coal has increased sharply and is dependent upon the point of origin and negotiated contract terms. In one instance the contract price of coal had increased from $10.50/ton in 1972 to $19.25/ton in 1974, with purchases made on the basis of a 1-year contract. A second firm purchases one-half of its anticipated coal requirements on the basis of a 5-year contract. In 1974, the contract price was $17.50/ton and had increased to $27.50/ton in early 1975. The remaining coal requirements are purchased on the open market and, in 1974, the spot price was about $40/ton and had declined to $31/ton in early 1975. Purchases are made on the open market on the premise that, historically, spot prices had been lower than contract prices. Within the past year or two, this relationship no longer existed, and the opinion was expressed that it may not occur again. Although the price of coal has escalated rapidly, availability problems are not anticipated in the immediate future.

Wide-scale conversion from natural gas and petroleum-based fuels could create shortages of coal supplies. Time would be required for the coal industry to obtain necessary capital and additional mine openings.

Trends in Emissions

To date, the cement industry has been able to comply with local, state, and Federal emission requirements. The types of emissions have been previously discussed, as well as methods of control. The method for controlling particulates is primarily the use of baghouses. These systems trap particulate matter that evolves primarily from the kiln and the clinker cooler. Electrostatic precipitators have been installed on a limited basis, but were found to be less satisfactory than baghouses. Corrosion of the unit and water disposal were two of the main problems encountered.

Disposal of the particulate matter, after collection, is a major problem in the industry. One of the companies contacted during the course of the field survey indicated that it must dispose of 650 tons of particulate waste per day and this is expected to double over the next 10 years. The material must be hauled by truck to suitable landfill sites. In some states, the landfill site must be specially prepared to prevent seepage of salts into substrata water. In many instances the expense of equipping an older kiln could not be economically justified and these have been phased out of service.

Not all of the particulate matter collected can be recycled into the raw material stream; this is especially true if low alkali cement is being made. The alkali content of low-alkali cement cannot exceed 0.6%/ASTM standard. It was suggested that, if this standard were revised upward to 1.5%, all of the collected particulate matter could be recycled and the problem of landfill disposal would be solved. The alkali salts react with the aggregate used in the final concrete mixture, and the cement manufacturer has no control over the type of aggregate used. The opinion was given that the increased alkalinity would not affect the quality of the cement.

Currently, emissions of SO_x and NO_x are not a major problem for the industry. Emissions of SO_x are controlled primarily by the use of low-sulfur fuels and controlled burning practices. The sulfur contained in the waste-heat stream reacts with the particulates collected and the raw materials as they are fed into the kiln. As a result the suflur emissions are collected along with the particulates in baghouses. The efficiency of this method of collection would be reduced noticeably if the industry would be forced to utilize fuels of higher sulfur content than those presently being used. About 50% of the SO_2 formed is collected in the baghouse because of the reactions with the alkaline particulates. NO_x emissions are not considered to be a major problem to the industry in the absence of legislation establishing minimum standards.

It is anticipated that the industry, as a whole, will have to spend $280 million to be able to comply with new 1973-1975 EPA standards.

Energy Cost of Emission Compliance

The cost of emission compliance, in terms of energy expended, is not readily quantifiable and is subject to many variables that should be evaluated on an individual plant basis. Included in such an assessment should be the energy requirements of the control equipment and the secondary units required to service the primary control device.

The energy required to operate the primary equipment is generally in the form of electrical power. This power is used to drive air-circulating equipment such as fans for the purpose of moving air through baghouses and other collection devices. It should be noted that, over the past 25 years, energy consumption in the form of fossil fuel, primarily in the operation of the rotary kiln, has shown a decline. However, over the same period, the consumption of electricity has remained steady at about 130 kWhr/ton of cement produced. This has been partially attributed to air pollution control equipment requirements. Estimates received during the course of field interviews regarding additional power requirements for primary pollution control devices were in the range of 5% to 15%. By applying the estimated range to the 130 kWhr mentioned above, the amount of energy required is from 6 to 17 kWhr/ton of cement produced.

An example of the secondary equipment operation required to service primary equipment is the trucks needed for hauling collected particulate matter from the baghouse or other collection device to landfill sites. As time passes, the distance traveled increases as nearby sites are filled. Fuels required for this are diesel fuel and/or gasoline, depending on the type of trucks used. The amount of energy consumed in this application is not available for this report.

The legislation pending, such as the establishment of an NO_x standard, can increase the amount of energy required to power pollution abatement devices. On the other hand, greater recycling of collected particulate matter into the raw material stream can reduce the energy consumed in this area.

Analysis

The potential for reducing energy consumption and air pollutant emissions in the cement industry is very great. In most instances, the industry is well aware of this potential. However, because of economic restraints, it is expected that this potential will be realized only after an extended period of time. It is significant to note that cement manufacturing in the rest of the world is far more efficient than in the United States, a fact that can, in part, be attributed to the premium placed on fuels outside the United States. Because most of the process modifications discussed above for reducing energy consumption are already in use in other countries, further technological development does not appear to be required.

With respect to air pollutant emissions, the industry's primary concern is with particulate emissions. Control methods are costly in terms of both economics and energy consumption. Because of the expense involved in purchasing and fitting pollution abatement equipment to existing facilities, many of the older facilities are being shut down rather than being converted. The collection of particulates in control devices creates an additional problem — that of disposal. Currently, this material is used for landfill, a very costly solution. More than one company suggested that the standards for product quality could be altered without affecting the characteristics of the final product. Specifically, by increasing the maximum allowable alkali content in the final product, a greater amount of particulate matter could be recycled, reducing cost and reducing energy by the amount required to transport this material to the landfill areas.

SO_x emissions do not present as severe a control problem as particulates, primarily because of the chemical reaction inherent in the burning process, which act to remove SO_x from the effluent stream. In general, SO_x control does not require any substantial add-on equipment. Consequently, control of SO_x should not result in increases in energy consumption. In fact, the use of preheaters, as discussed above, not only increases the efficiency of cement manufacturing with the potential of reducing energy consumption by up to 50%, but also acts to precipitate SO_x out of the exhaust gases, preventing expulsion into the atmosphere. The fact that preheaters are not widely used in this country is again a matter of economics and raw material composition. However, in spite of the economics, a few companies are currently using preheaters, suggesting that their application is greatly dependent upon local conditions.

Not too much is known about NO_x emissions from cement kilns. But considering the process temperatures involved — greater than 1500°C in some cases — the potential for large quantities of NO_x emissions is great. As discussed in other sections of this report, NO_x formation is a temperature-dependent phenomenon. Process modifications that increase flame temperature without improving heat transfer to the process load will almost certainly result in increased NO_x emissions. Conversely, adequate removal of the additional heat resulting from the applicable process modifications should maintain NO_x emissions at their current level.

Of the modifications deemed to be near term, only the use of oxygen enrichment has any great potential of increasing air pollutant emissions, primarily NO_x. While in some applications in other industries, for example, glass melting, oxygen enrichment can be used without increasing NO_x emissions. However, due to the different type of load in the cement industry and the different patterns of heat transfer, it is not clear that NO_x would not increase with the implementation of oxygen enrichment. None of the other modifications classified as near term are expected to affect air pollutant emissions.

The potential effect of implementation of long-term modifications for reducing energy consumption on air pollutant emissions is substantial. Conversion to the dry process will increase the potential for increased particulate emissions. Based on current available data, if uncontrolled, particulates would increase by more than 10%. The technology is available for controlling particulates, but application of these control devices will increase energy consumption. Whether the increase will totally cancel the reduction in energy consumption achieved by converting to the dry process is not determinable in this program.

Implementation of the vertical kiln can be expected to substantially reduce NO_x emissions. The mechanism of operation is such that heat transfer to the load is very high, and peak temperatures are lower than required to obtain the formation of NO_x in large amounts. The vertical kiln may also affect SO_x emissions. As discussed above, the process requires the use of low-volatile fuels, such as coal, which may contain substantial amounts of sulfur. While it is true that SO_x emissions are eliminated, to a large extent, from the flue gases by absorption, there is no data for how much is removed in this manner. By increasing the amount of SO_x that must be removed, the potential for exceeding the absorption capacity of cement reactants is high, resulting in an increase in SO_x emissions. Control devices added on to remove the excess SO_x emissions from the effluent will require additional energy, reducing the attractiveness of the vertical kiln as a method of reducing energy consumption.

The net result of this analysis is that implementation of energy-conserving process modifications can be accomplished without increasing air pollutant emissions. It is not clear to what extent energy utilization will be reduced. Control devices required to maintain the emissions at the present level or to reduce the level may consume enough energy by themselves to offset the reductions in energy consumption by implementing the specific process modifications.

Recommendations

It has already been noted that the primary obstacle to widespread acceptance of energy conserving process modifications in the cement industry is the lack of economic feasibility. To this extent, there is little that can be done to speed up implementation. Even the industry agrees with this summation of the situation. Nevertheless, there are several areas requiring data, which will allow for a more accurate evaluation in terms of the direction to take, when the economics for making the necessary choices are favorable.

As in the other industries studied, the first step in reducing emissions is to determine what the emission rates are at the present time. Specifically, a program should be undertaken to measure NO_x emissions from the various heating processes in the industry; this will primarily involve sampling from dryers, preheaters, and kilns. This information is essential and vital to the success of other programs in this area.

The study of this industry has revealed that, underneath the economic objections raised by the industry, there are some questions with respect to technical feasibility of the suggested modifications. But, as already pointed out, most of these modifications are being satisfactorily used elsewhere in the world. Rather than set up demonstration facilities in this country, we recommend that programs be undertaken to collect the necessary operating data from plants already in operation in other countries. These plants afford the opportunity for collecting not only fuel data but pollution data as well without the great cost of a demonstration facility. Such information would be most beneficiel in determining the direction to take in dealing with energy and emission problems, when the available technology becomes more economically feasible.

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Aluminum Industry — State-of-the-Art

The aluminum industry can be broken down into two major segments — primary and secondary manufacturing. The primary aluminum industry is concerned with the manufacture of aluminum using the basic raw material bauxite, converting it to alumina, and in turn processing the alumina into aluminum by means of the Hall-Herault electrolytic process. The secondary aluminum industry is concerned primarily with the recovery of aluminum from scrap by melting down the scrap and removing impurities to obtain the refined product.

The aluminum industry is growing at a greater rate than any of the other nonferrous metal industries, doubling its production output every 10 years. In the primary aluminum industry alone, production is expected to increase from 4 million tons in 1970 to more than 12 million tons in 1985.

Primary Aluminum Production

A simplified flow sheet for the production of primary aluminum by the Bayer-Hall process is shown in Figure 11, which includes the manufacturing unit operations for carbon anodes and cathodes. In general, primary aluminum production can be subdivided into three operations: mining the bauxite, refining the bauxite into alumina, and smelting the alumina into aluminum. Each of these operations is described briefly below. However, it should be noted that the major operation in primary aluminum production is not the focal point of this study as it does not involve the direct combustion of fossil fuels. As will be seen, most of the direct fossil fuel consumption is in the refining, melting, and reheating operations.

Mining

Bauxite is the ore from which aluminum is produced. Because most bauxite lies at or near the surface, it usually is mined by open-pit methods. After the ore is dug up, it is transferred by truck and rail to a point of processing. There the bauxite is ground down to uniformly sized particles and passed into a rotary kiln in which excess moisture is removed.

The drying process is a relatively low-temperature process; it requires temperatures of only 1100°F. Consequently, heat losses are minimized and energy utilization efficiency is relatively high — about 40%. The energy consumed in drying is 1.0 million Btu/ton of ore dried. Drying accounts for only a small percentage of the energy consumed domestically by the aluminum industry because only 15% of the bauxite consumed in the U. S. is obtained from domestic sources. Thus, in 1971, only 2.3 trillion Btu, less than 1% of the industry's total annual energy consumption, was used for drying.

Refining

The refining of bauxite to obtain alumina is achieved by the Bayer Process. The objective of this process is to separate out the impurities, which include iron oxide, silica, and titanium dioxide.

The first step in the Bayer Process is digestion of the bauxite into a solution of hot caustic soda. The dried bauxite is mixed in slurry tanks with a strong caustic soda solution. The mixture is pumped into large digesters in which it is heated with steam under pressure. The alumina in the bauxite is dissolved in the caustic soda, forming a sodium aluminate solution. The

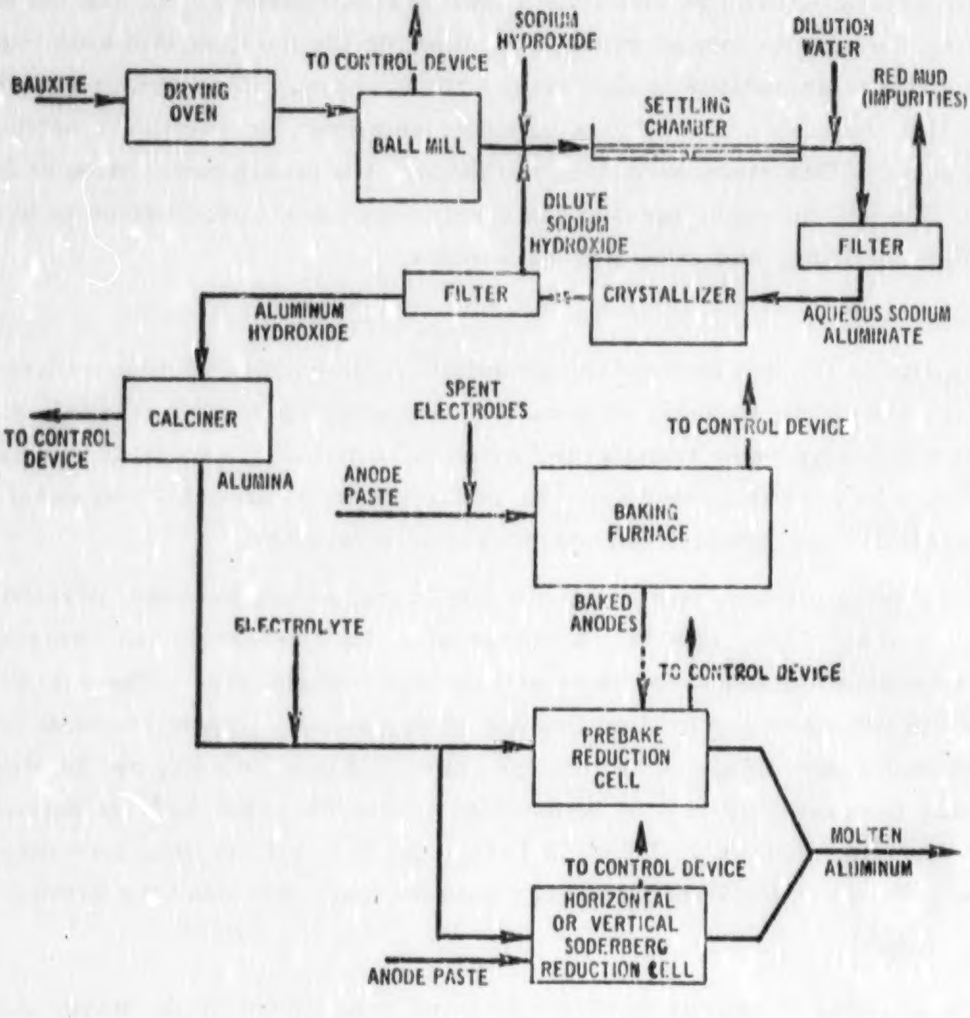

BAUXITE
DRYING OVEN
TO CONTROL DEVICE
SODIUM HYDROXIDE
BALL MILL
DILUTION WATER
SETTLING CHAMBER
RED MUD (IMPURITIES)
DILUTE SODIUM HYDROXIDE
FILTER
FILTER
CRYSTALLIZER
ALUMINUM HYDROXIDE
AQUEOUS SODIUM ALUMINATE
CALCINER
TO CONTROL DEVICE
SPENT ELECTRODES
TO CONTROL DEVICE
ALUMINA
ANODE PASTE
BAKING FURNACE
BAKED ANODES
ELECTROLYTE
TO CONTROL DEVICE
PREBAKE REDUCTION CELL
TO CONTROL DEVICE
MOLTEN ALUMINUM
HORIZONTAL OR VERTICAL SODERBERG REDUCTION CELL
ANODE PASTE

Figure 11. SCHEMATIC DIAGRAM OF PRIMARY ALUMINUM PRODUCTION PROCESS

impurities, which are insoluble, remain as solids. The mixture is passed through a series of pressure-reducing tanks and filter presses. Cloth filters hold back the solids — known as "red mud" — but allow the liquid, which contains the dissolved alumina, to pass.

At many plants, the red mud is discarded, but at some — where lower grade ores are refined — this mud is sintered with limestone and soda ash to recover a sodium aluminate solution. This solution then is returned to the digesters for processing through the remaining steps of the refining process.

After the solution containing the alumina passes through the filters, it goes into a cooling tower and then into precipitators, which are steel structures resembling farm silos. As the solution cools, it is seeded with sizable amounts of crystalline alumina hydrate to hasten crystal separation. Eventually, a precipitate of hydrated alumina settles out of solution. This precipitate is filtered from the solution, washed, and then heated in kilns at 1800°F. The crystals are dried, and the water is driven off, leaving commercially pure alumina. The dried alumina is shipped to an aluminum smelter for reduction.

The Bayer Process consumes from 10 to 15 million Btu of thermal energy per ton of alumina produced. Natural gas is the preferred fuel; consequently, most Bayer Process plants are located in areas of lower cost natural gas. Further discussions of this operation will be minimized since the technology of the rotary kiln, the primary energy consuming equipment in the Bayer Process, is similar to the technology of the cement industry, discussed elsewhere in this report.

Smelting

Smelting is the process that breaks alumina down into its two components, aluminum and oxygen. The basic smelting process is the Hall Process, which has been used by the industry since 1886. In this process, alumina is dissolved in a bath of molten cryolite — sodium aluminum fluoride — in large electric furnaces. These pots, as the furnaces are called, are deep rectangular steel shells lined with carbon and connected electrically in series to form a "potline."

High-amperage, low-voltage direct current is passed through the cryolite bath — by means of carbon anodes suspended in each pot — to the bottom of the pot, which serves as the cathode. The molten aluminum formed as a result of this electrolysis goes to the bottom of the pot, and the oxygen combines with the carbon anode to release carbon dioxide. The layer of molten aluminum that covers the carbon lining at the bottom of the pot becomes the cathode. Additional alumina is added to the bath to replace that consumed in the reduction process. Heat generated by the electrolysis maintains the cryolite bath in a molten state, so that the additional alumina charges are dissolved. Periodically, molten aluminum is siphoned and cast into ingots or alloyed. The resulting aluminum is at least 99.5% pure.

The primary source of energy for this process is electricity, which is consumed at the rate of 55 to 60 million Btu/ton of aluminum produced. This does not include the fuel consumed for generating the electricity.

The three types of pots used in this process are distinguished by the type of anode configuration: prebaked, horizontal-stud Soderberg, and vertical-stud Soderberg. The major portion of aluminum produced in the U. S. (61.9% of 1970 production) is processed in prebaked cells. In this type of pot, the anode consists of blocks that are formed from a carbon paste and baked in an oven prior to use in the cell. These blocks are attached to metal rods and serve as replaceable anodes. As the reduction proceeds, the carbon is gradually consumed. The rate of consumption is 0.45 to 0.55 pound of electrode per pound of aluminum produced, which is typical of all three types of pots.

The second most commonly used pot (25.5% of 1970 production) is the horizontal-stud Soderberg. This type of cell uses a continuous carbon anode in which a mixture of pitch and carbon aggregate is periodically added at the top of the superstructure, and the entire assembly is moved downward as the carbon burns away. The cell anode is contained by alumunum sheeting and perforated steel channels, through which electrode connections, called studs, are inserted in the anode paste (the pitch and carbon aggregate mixture). As the baking anode is lowered, the lower row of studs and the bottom channel are removed, and the flexible electrical connectors are moved to a higher row.

The vertical-stud Soderberg is similar to the horizontal-stud pot, except that the studs are mounted vertically in the cell. The studs must be raised and replaced periodically, which is a relatively simple operation.

Anode preparation constitutes a major energy-consuming process in the primary aluminum industry, which is often overlooked as a secondary operation. However, depending on the type of anode used, energy consumed for anode baking varies from 1300 Btu to 5700 Btu/pound of aluminum metal produced. Each anode system currently accounts for about 50% of the aluminum produced, resulting in an estimated 28 billion Btu of energy consumed annually for anode baking.

Secondary Aluminum Processes

Secondary aluminum processing is essentially the process of remelting aluminum. The equipment used is essentially the same as that used for melting in the primary aluminum industry. Thus, the following discussion of the melting processes is applicable to both segments of the industry.

Melting and Reheating

The types of furnaces generally used for the melting of aluminum are —

- Large and small stationary and tilting reverberatories
- Holding furnaces (reverberatory)
- Tilting, barrel-type furnaces
- Stationary and tilting crucible furnaces
- Dry hearth melters.

Primary aluminum melting furnaces range from small crucible furnaces for foundry use, called heading pots, to very large reverberatory melters having a capacity of 25 to 80 tons per charge. Small furnaces of the ladle-crucible or tilting-crucible types and small reverberatories of up to 10,000-lb capacity are usually based on a standardized-design from equipment builders. Some of the largest producers of aluminum and aluminum-alloy products design and build their own melters, ranging up to 80-ton capacity. Others may purchase even their largest melters from equipment builders, but generally these must be designed to meet the requirements of a particular casting facility.

Although some continuous melters are in use, normal practice is to melt on a cyclic basis because of the need to arrive at a design compromise involving caster layout, need to adjust chemical analysis, arrangement of other plant equipment, building layout, type of charge, operating efficiency, and production requirements. Firing rates on a melting furnace are usually quite high so as to obtain the fastest melting-rate possible without excessive metal loss or refractory damage. On the other hand, after melting is complete, the metal is cleaned by passing mixtures of fluxing gases through the molten metal and is brought carefully to the exact pouring and casting temperature in as quiescent an atmosphere as possible to avoid oxide formation and metal loss. This requires a very close control over heat input. Because of the major differences between relative inputs for melting and holding and the respective combustion requirements, two different furnaces are usually used for the large-scale melting installations: one for melting, called a breakdown melter, and a second for refining and holding, called a holding furnace.

Melting-Furnace Design

A typical large-scale, reverberatory aluminum melter is quite similar in general design to the steel mill open-hearth furnace. It is usually a rectangular, refractory-lined box with burners at one endwall and charging doors above the metal line along one side. Furnace size is dictated by two key factors: melting rate and capacity. The melting rate is determined by the thermal head between a) the metal refractory surfaces and the flame, and b) the heat-transfer area or area of the surface of the metal bath. Metal capacity is determined by the depth of metal below the metal line. The melting rate can be increased by using a sloping dry hearth from which molten metal drains to a holding bath, but this design tends to increase metal loss.

Design practice for reverberatory melters varies considerably from company to company. One of the major aluminum companies prefers the rectangular design, and regards a length-to-width ratio of 2 as optimum geometry for the 25 to 50 ton capacity melters and a square or round melter for smaller reverbs of up to 5-ton capacity. Another major producer uses a tangentially or radially fired round melter with sidewall charging, on the basis that the best design geometry has the largest volume-to-wall ratio.

Aluminum melters are designed for melting rates as high as 62 lb/sq ft-hr, taking only melting into account. Allowing for charging, holding, and discharging, a good general-design number is 35 lb/sq ft-hr. Dry-hearth melters can produce at a rate of 100 lb/sq ft-hr, but are not used for high-quality aluminum-alloy production because of high oxidation loss.

Secondary melters (metal reclaiming) are generally designed for lower melting rates, about 15 to 20 lb/sq ft-hr. In these furnaces, fluxing is usually done in a charging well, a compartment separated from the main melting and holding chamber by a partition wall and submerged throat. The melting period in these furnaces is only about 40% of the overall cycle.

Energy Requirements

Approximately 75 million Btu of energy is consumed in an aluminum plant for power and heat in the production of 1 ton of aluminum. However, fossil fuels also are consumed in the manufacture of the carbon electrodes used in the electrolytic process. And finally, because electricity is the primary form of energy consumed, fossil-fuel consumption for electricity generation also should be considered. Specific process energy requirements have already been presented for primary aluminum manufacturing — that is, the Bayer-Hall process — and will not be discussed further. Attention can thus be focused on the combustion-oriented processes, specifically, melting and reheating.

Overall melting efficiency for a large (25 to 50 ton) aluminum melter is normally 15% to 20%, including time required for charging, holding, and discharging. Efficiency might be as low as 10% for some special alloys and, at the other extreme, as high as 50%. Current melting practice is to melt down as rapidly as possible with high input rates to achieve maximum productivity, which has an adverse effect on fuel efficiency. Peak gas temperature entering the flue is now about 2800°F or higher; a few years ago, it was about 2200°F. Some of the factors affecting fuel efficiency are type of alloy, amount of metal loss due to oxidation, type of charge, charging practice, furnace geometry, burner and flue arrangement, and ratio of melting time to total time between charge and pour.

The relation between fuel consumption per pound of metal heated and fuel efficiency can be shown as follows:

Efficiency, %	Natural Gas, CF/lb
15	3.37
20	2.53
25	2.02
35	1.44
50	1.01

A typical fuel consumption for large melters is 3 cubic feet of natural gas per pound of metal, giving an efficiency of 15%.

Efficiency for the smaller crucible melters is about 5% to 10%. The higher efficiency obtained in reverberatory melting is attributable to direct heat transfer from the flame and surrounding refractory surfaces to the metal surface, whereas in crucible furnaces heat must be transferred through a partition wall.

Crucible melters heated by electric induction are reported to reach an efficiency of 67% to 73%. On the basis of an average efficiency for power generation of 32%, the overall fuel efficiency for electric-induction melting will be only about 22.4%.

Fuels used in the melting and reheating processes include natural gas, LP gases, distillate and residual fuel oils, and electricity. However, natural gas is the preferred fuel. According to industry representatives, the use of oil requires modifications in operations that decrease the efficiency of operation. This decrease in efficiency is attributed to the relationship between the size of the combustion space in the furnace and the flame. Because the oil requires a larger combustion zone than gas, the relationship is changed to the detriment of fuel-utilization efficiency.

Air Pollutant Emissions

Air pollutant emissions originate from several processes in an aluminum manufacturing plant. The most objectionable and most difficult to control are those from the potlines. Aside from carbon monoxide and carbon dioxide, which are released as a result of the reaction of oxygen from the aluminum with the carbon anode, emissions from the potlines include sulfur dioxide, derived from the sulfur in the petroleum coke and materials; hydrogen fluoride gas, the result of hydrolysis of some fluoride salt vaporization; alumina, cryolite, and aluminum fluoride dusts; and minor quantities of a number of other pollutants. However, this program is concerned with combustion-related emissions, thus excluding the potlines from further consideration. The pertinent sources of emissions are the calcination operation by way of the rotary kiln, and the melting and reheating processes, and the anode baking operation. Table 13 summarizes the available information on the emissions from aluminum manufacturing processes. It should be noted that many of the specific pollutants listed are peculiar to the particular process and unrelated to combustion. For example, most of the air pollutants in the effluent stream from an open-flame, reverberatory-type furnace used in remelting aluminum scrap are the result of residual material, such as grease and oil, on the surface of the scrap. Given proper control of the combustion process itself, combustion-related emissions are virtually nonexistent. The reason for this is clear. The primary fuel used in secondary aluminum processing is clean-burning natural gas, which precludes the emission of particulates and SO_x. NO_x emissions are not a problem because most of the process temperatures are lower than the minimum required for formation of large amounts of NO_x. However, given the trend toward higher melting rates requiring higher temperatures, NO_x emissions could become a problem.

The industry does not operate pollution-free. Stack emissions are controlled in several ways. Many secondary aluminum producers have resorted to natural gas-fired afterburners followed by venturi scrubbers for control of chloride and fluoride emissions or baghouses for control of particulates. Electrostatic precipitators are not generally used where the emissions are high in carbon content because the carbonaceous materials cause the ESP unit to short out. It should be noted that the use of this equipment for pollution control adds substantially to the energy used by a company. For example, the use of baghouses consumes about 1000 Btu/lb of product and the afterburners consume about 2000 Btu/lb of product.

Trends in Aluminum Process Modifications

Because the Hall-Heroult electrolytic process is the major energy-consuming process in the manufacture of aluminum, great effort is made to improve its efficiency. The most significant improvement in this area has been the development of a new smelting process that consumes 30% less energy than the current technology. However, there are modifications that can be applied to other processes in the industry, which, while not quite so

Table 13. AIR POLLUTANT EMISSIONS FROM ALUMINUM MANUFACTURING PROCESSES

Process	Particulates	Emissions SO_x	Emissions NO_x	Hydrocarbons
Bauxite Grinding	6 lb/ton bauxite	NA	NA	NA
Calcination of Hydroxide	200 lb/ton alumina	NA	NA	NA
Soderberg Cells				
Horizontal Stud	144 lb/ton aluminum	NA	NA	NA
Vertical Stud	84 lb/ton aluminum	NA	NA	NA
Prebake Cells	63 lb/ton aluminum	NA	NA	NA
Anode Preparation	NA	NA	NA	NA
Sweating Furnaces	32 lb/ton charged	NA	NA	NA
Refining Furnaces (Secondary Operations)				
Reverberatory	4 lb/ton charged	NA	NA	NA
Pot	2 lb/ton charged	NA	NA	NA
Induction	--	--	--	--

Note: NA — Emissions known to occur but quantities not available.

spectacular, can result in substantial reductions in energy.

Flash Calcining

Table 14 summarizes the available process modifications and the potential for reducing fuel consumption.

Table 14. SUMMARY OF AVAILABLE PROCESS MODIFICATIONS AND THEIR POTENTIAL FOR REDUCING FUEL CONSUMPTION

Process Modification	% Reduction in Fuel Consumption
Flash Calcination	20 to 30
Stack Charging	5 to 10
Hot-Metal Recirculation	5 to 6
Recuperation	20 to 25
Oxy-Fuel Melting	10 to 15
Excess-Air Reduction (20% to 10%)	5
Infrared Heating (Crucible Melting)	20 to 25

Using the fundamental principles of fluid-bed and dispersed-phase technology, a flash calciner improves heat exchange and reduces heat losses. This process, to be used in place of the rotary kiln calciner in the conversion of bauxite to alumina, consumes up to 30% less energy than the rotary kiln process. The process has been successfully installed in several bauxite refineries around the world, with the expectation that more will follow. It should be noted that currently most of the alumina used in the U. S. is imported. There is a trend toward refining the bauxite in this country. If this trend continues, it is likely that this process will gain widespread usage in a relatively short period of time because this phase of the industry would be developed from the ground up — that is, independent of the phasing-out of any existing equipment.

Stack Charging

In some of the large aluminum melters, the charge is placed on a sloping hearth at the base of the stack, as shown in Figure 12. The high-temperature flue gas transfers heat to the charge on the "dry hearth" by convection and raises the ingot temperature to the 600° to 750°F range before the ingot is pushed into the molten bath. Advantages of this charging system are an increased melting rate and a higher melting efficiency. It is estimated that fuel efficiency can be increased by about 5% to 10%. With this system, scrap is generally charged in a separate well.

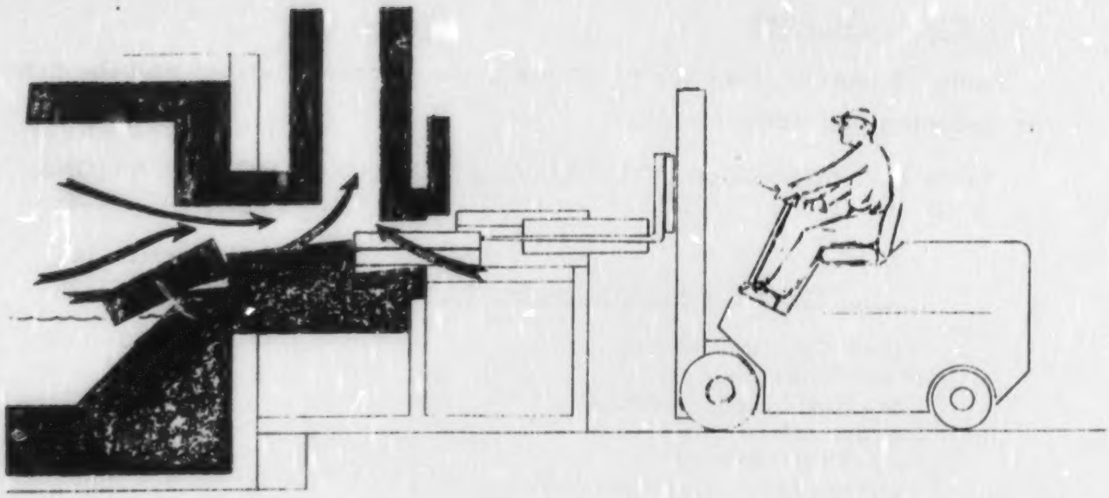


Figure 12. ALUMINUM MELTER WITH SLOPING HEARTH

Hot-Metal Pumping

Development of hot-metal pumps with refractory internals has made possible several improvements in reverberatory melting, particularly in better utilization of charging wells for high-surface-area scrap such as chips and foil. The increased bath velocity due to the pumping action increases the rate of heat transfer to the scrap, thereby melting it faster and reducing the time that the surface area is exposed to oxidation. Metal loss due to oxidation is reduced by 50%. In addition, either the overall melting rate can be increased by 15% to 25% or the fuel efficiency increased by 5% to 6% at the same melting rate.

Recuperation

Combustion-air preheat by recuperation of waste heat in the flue gases is seldom used in the U. S. because of the low cost of natural gas. However, it is used extensively in Europe, where fuel prices are considerably higher. Because only 20% to 40% of the total melting cycle is required for the actual melting operation, recuperation has been difficult to justify economically. Also, for holding chambers where fluxing is done in the melting chamber, the stack gases will contain hydrochloric acid and other corrosive components that reduce the service life of normal recuperator internal parts. However, many of the largest melters are installed with separate holding furnaces, and, at the higher prices anticipated for natural gas and fuel oil, it will be possible to justify the installation of recuperators. Preheating combustion air to the 600° to 800°F range will give a fuel savings of 20% to 25%, as the following data demonstrate:

Air Preheat Temperature, °F	% Fuel Saving
400	13.5
600	19.8
800	25.5
1000	30.6
1200	35.0
1400	39.0

Oxygen-Fuel Melting

In recent years, tests on primary and secondary aluminum melters have proved the effectiveness of using auxiliary oxy-fuel burners to reduce meltdown time, metal loss, and fuel consumption. In remelting, where 97% of the charge is scrap, a reduction in meltdown time from 2 hours to 1 hour was achieved. Charge weights averaged 46,000 lb, and oxygen consumption was 712 SCF/ton melted. The melting rate was increased by an average of 55% and the melt loss reduced by 26%. Relative combustion efficiency was 48% during the period of oxygen burning and 29% during air burning. The oxy-fuel roof-mounted burners in this plant were used as auxiliary burners to back up four air burners.

Improved Air/Gas Ratio Controls

Close control over excess air is a critical element in maintaining combustion efficiency, particularly for furnaces in which combustion products enter the flue ports at a temperature above 2000°F. In aluminum melters, flue-gas temperatures typically range from 2200° to 2800°F. With burner designs that give good control over air-gas mixing, only 5% to 10% excess air is required to obtain maximum heat release and high flame temperature, but many melters run with 20% or more excess air. The problem of controlling excess air is quite difficult because of the large reduction in input required for firing at maximum rate during melting and for holding at minimum input after melting is completed. A burner turndown of more than 10:1 is required, and a typical balanced pressure-metering orifice system cannot maintain this ratio over such a large turndown range. Also, a sufficient flame velocity must be maintained so that combustion products are not short-circuited to the flue when it is located directly below the burners. One way to overcome this problem is to use several smaller burners rather than one or two large burners and to turn off some of the burners when a turndown greater than about 8:1 is required. Another method, used on steel mill soaking pits, is to use a 2-in-1 or 3-in-1 burner in which the air housing is compartmented so that a very large turndown range can be obtained by reducing the burner area.

Fuel inputs on the largest melters range up to 40 million Btu/hr, and for many of the large melters, installation of a control system that maintains a precise air/fuel ratio by controlling stack-gas oxygen concentration should be justifiable. This type of control system is also effective when combustion-air preheat is used.

Infrared Heating — Crucible Melting

Extensive tests run by the Research Department of the Consolidated Natural Gas Service Co. have shown that the efficiency of crucible melting of lead, zinc, and other metals of low melting points can be materially increased by using infrared radiant-heating elements around the crucible. Efficiency with infrared heating has been in the 30% to 40% range, compared with the 15% to 20% normal range obtained with conventional firing methods. The melting temperature of aluminum is somewhat higher (1220°F), but a substantial improvement should be obtained for aluminum melting — say a 20% to 25% reduction in fuel requirement.

Trends in Energy Utilization

Because the potlines constitute the major energy consuming process in the manufacture of aluminum, most of the efforts for reducing energy consumption are in this direction. With respect to this process, implementation of the new Alcoa process for smelting can be expected to account for the most dramatic reductions in energy consumption in the long term.

On the other hand, the potential for reduction in energy consumption by fossil-fuel fired processes is also large, but is often downrated in importance when compared with the potlines. Of the process modifications discussed above, only flash calcination, oxy-fuel melting, and improved air/fuel ratio control are considered by the industry to be significant in terms of reducing energy and even then not without some trepidation. For example, while there are companies using oxygen in their melting operations, it is not deemed to be particularly economical and is thus used only when there is a demand for aluminum in excess of the normal production capacity. Flash calcination, although fully developed, is considered long term in that its implementation will occur only with the phasing-out of existing rotary kilns. Furthermore, even if it were implemented immediately, it would only have minimum impact on the total energy consumption pattern because most of the bauxite consumed by the industry is actually processed outside the U. S.

The use of air/fuel ratio control equipment is one area of modification in which implementation can be achieved in a short period of time with minimal expenditures. In several companies, evaluation and installation of this equipment is a continuing process. As such, on an industry-wide basis, the impact of such implementation will be relatively small.

Recuperation, as attractive as it appears to be for reducing energy consumption, is not viewed favorably by the industry at the present time. Two reasons given for this attitude are that the economics do not as yet justify its use and the effluent is corrosive, thus shortening the lifetime considerably. Only as fuel prices increase will there be a change in attitute toward recuperation.

Energy Use Based on Availability

As indicated above, the use of natural gas is predominant and preferred in the manufacture of aluminum. However, shortages of natural gas are causing the industry to switch to alternate fuels, primarily fuel oil. According to the companies interviewed, the use of oil significantly reduces the efficiency of fuel utilization, although none of the companies were able to actually quantify the reduction.

In addition, although considerably in the future, there is a trend developing to use coal as a fuel in aluminum melters. From the standpoint of product quality, there does not appear to be any reason not to use coal. In fact, during the 1930's, most reverberatory aluminum melters were coal-fired.

Trends in Emissions

According to industry representatives, melters fired with natural gas, propane, or oil with an acceptable sulfur level do not require stack-gas cleaning or scrubbing to meet existing pollution codes. However, a shift toward the use of coal requires the development of a compact, efficient, and cost-effective process to remove SO_2 from stack gases in order that existing codes on SO_2 emissions are met. In addition, shifting to coal firing will require installation of some kind of stack-gas cleaning system for removal of fly ash from the effluents. In the alternative, treatment of the coal prior to combustion to remove sulfur and reduce fly ash, such as in solvent refined coal, may be a more attractive solution as far as this industry is concerned.

According to industry representatives, process modifications for purposes of reducing energy consumption should have no effect on the ability of the industry to meet current existing standards. Most prominent on the list of modifications is the flash calcination process. According to uses of the process, there has been no difficulty in meeting local control regulations. However, no information concerning the pollution control equipment used was offered.

As indicated above, the industry is not concerned with NO_x emissions primarily because of the absence of standards. There is no available data, but considering that most processes operate below the temperature required for generating large amounts of NO_x, NO_x should not be a problem at the present time. With the implementation of greater oxygen-enrichment facilities and with the installation of recuperators, NO_x emissions will tend to increase as process temperatures increase. This is, however, deemed to be a long-term effect.

Analysis of Data

In general, analysis of the available data indicates that implementation of most of the energy-conserving process modifications should have only minimal impact on air pollutant emissions. This is dependent upon the use of adequate control measures as in the case of the flash calcination process. Clearly, the use of such devices will reduce the overall impact of the energy-efficient process on energy consumption; however, there is no data available to quantify the impact.

Conversion to coal, as discussed above, would have a significant impact on air pollutant emissions in the absence of adequate control devices. Even with suitable control devices, and assuming the pollution-free nature of the combustion process in this industry, emissions will probably increase. Whether or not the processes are actually free of pollutants in the effluent streams can only be surmised; but with adequate controls on the combustion itself and the use of clean-burning fuels at relatively low process temperatures, it is, in fact, likely that the processes comply with current regulations.

In the attempt to improve energy-utilization efficiency in the secondary aluminum industry, it is clear that NO_x emissions will be affected. As was indicated, when the process temperatures increase, NO_x emissions will also increase. One area that has had little attention is the use of afterburners as pollution control devices. As they are currently used, effluent gases as high as 1800° to 1850°F in temperature are being emitted into the atmosphere without any attempts at waste heat recovery. Clearly, the waste heat from these gases can be used to preheat scrap or preheat combustion air. An additional value is found in the heating value of the waste organic material which, if recovered, would allow some reduction in primary fuel utilization and eliminate a solid waste-disposal problem in those cases where scrubbers are used downstream of the afterburner to recover dry salts. However, it is unlikely that the afterburners themselves are contributing to the emission problem in the form of NO_x emissions. The operating temperatures are not high enough for large amounts of NO_x emissions to form. There are no data to substantiate this conclusion, and thus it must remain speculation until field investigations are made.

Recommendations

Under current conditions and relative to the specific area of concern — that is, the relationship between energy conservation and combustion-related air pollutant emissions — there are few areas of great conflict if it is assumed that NO_x emissions are low. It is possible, though, that this is illusory, based on insufficient data, primarily in the area of actual emissions. Consequently, the first recommendation must be to undertake a program for collecting data from operating facilities. This is particularly true in the case of NO_x emissions. Having obtained this data, a more precise evaluation of the effect of process modifications can be made.

The area that requires the greatest amount of development is waste-heat recovery. Programs should be initiated to solve the existing problems of recuperation, primarily the corrosion of the recuperators by the effluent gases, and the economics of operation. In developing systems, it is important that low-grade waste heat also be considered because much of the waste heat of the industry is in this category.

Oxygen is already used in melting, but only on a limited scale. Programs should be developed, as in other industries, to develop the true potential of this method for increasing fuel-utilization efficiency. As is other industries, a corresponding program would have to be run to determine the effects of oxygen on NO_x emissions.

These recommendations are generally in agreement with those of the industry and thus should not run into opposition. The industry is eager to cooperate, as evidenced by their participation in the FEA and Department of Commerce program, and make long-term commitments for voluntarily reducing energy consumption.

Petroleum Refining Fired Heaters — State-of-the-art

Petroleum refining is largely accomplished by distillation separation into intermediate feedstocks and products. The intermediate feedstocks require heating and thermal cracking or catalytic treating before separation of the desired products. This separation usually requires additional heating after the catalytic treatment or thermal cracking.

Total refinery energy consumption amounts to around 10% of the crude throughput. Most of this energy is consumed as fuel in fired heaters. The amount of energy consumption depends largely on the complexity of processing that takes place after the initial crude distillation separation. Generally, a gasoline-oriented refinery will have fuel consumption considerably greater than a distillate-oriented refinery. In the long run, the refinery output is controlled to meet consumers demand. This demand is for high gasoline production in the summer and fall seasons, with high distillate fuel production during the winter season.

Because of the diversity that exists among the various refineries currently in operation, it is not practical to do a detailed analysis of the industry on a process basis. Thus, the scope of this program was limited to an investigation of only fired heaters.

Fired heaters are used in many operations throughout the process of refining petroleum, beginning with the initial crude distillation unit, in which the lighter, more volatile components are separated from the heavier, less volatile components. The resulting fractions become the charging stock for the other operating units in the refineries. Several types of equipment can be used in the process; the basic types are shown in Figure 13. Typically, distillation occurs when heated crude oil is admitted into a fractionating column, which is tapped at several points, thus allowing continuous removal of the various boiling fractions, or products. The residue from this process may be submitted to vacuum distillation. When the fractions within the crude have small volatility differences or when it is desired to separate a higher boiling constituent from other components of a system of vapors and gases, additional distillations employing solvents or absorbers are used.

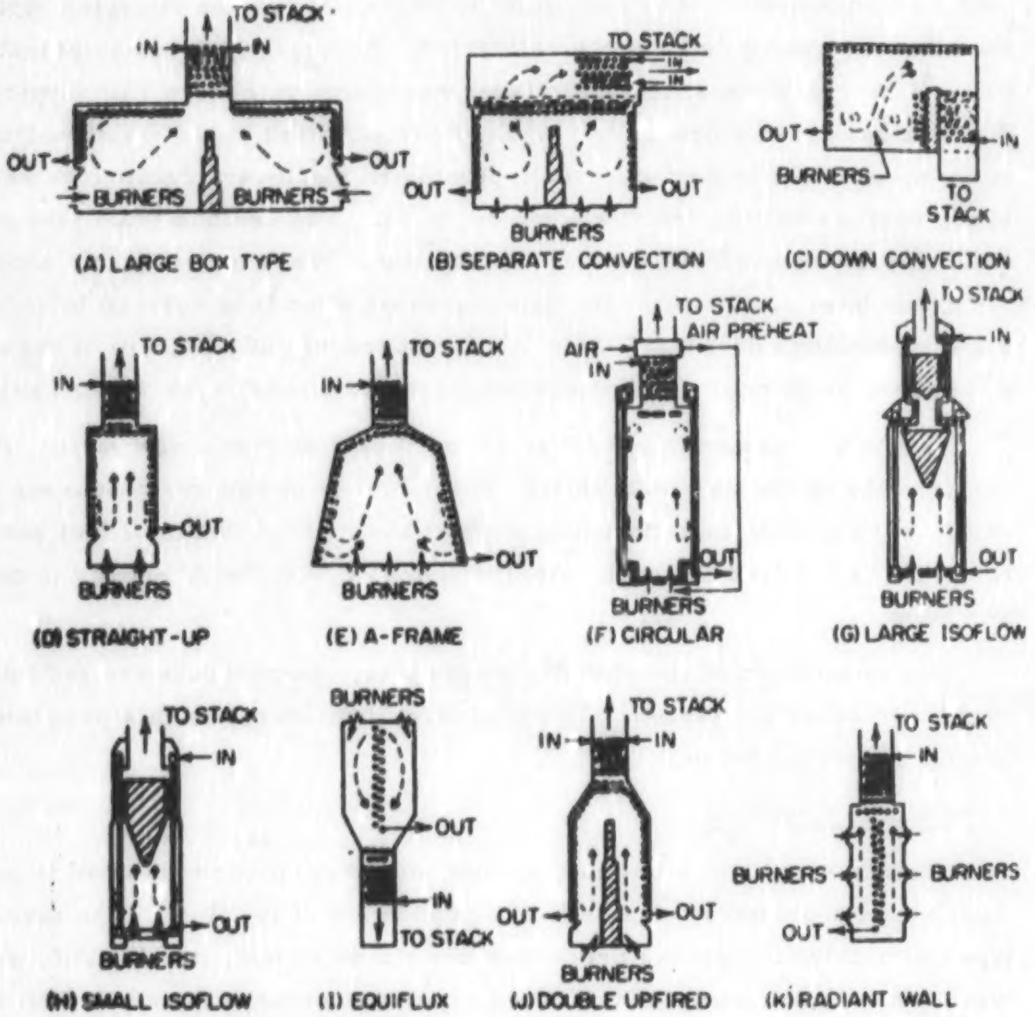
The energy consumption of a crude oil distillation process varies, depending upon the particular installation, but a review of several processes indicates that a typical installation consumes about 100,000 Btu of fuel per barrel of crude oil feed for heat. An additional 20,000 Btu of energy is consumed as steam.

Upon completion of the distillation process, the products are fed into any number of other processes. The processes considered in this program are briefly described below.

Catalytic Cracking

Catalytic cracking is one of the most important processes used in refineries. Its primary purpose is the production of gasoline. The three basic types of catalytic cracking processes are fluidized bed, moving bed, and fixed bed. At present, fluidized-bed cracking accounts for about 80% of the refinery catalytic cracking capacity, and moving-bed cracking accounts for the remaining 20%. The fixed-bed catalytic cracking process is virtually extinct.

In the fluidized-bed process, the reacting vapors (feed) are forced upward through a bed of fine granular material with finely divided solid catalyst evenly distributed throughout the system. This establishes a quasi-fluid suspension, in which the reacting vapors come in contact with the evenly distributed catalyst and undergo cracking. Upon completion of the cracking,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(A) LARGE BOX TYPE (B) SEPARATE CONVECTION (C) DOWN CONVECTION

(D) STRAIGHT-UP (E) A-FRAME (F) CIRCULAR (G) LARGE ISOFLOW

(H) SMALL ISOFLOW (I) EQUIFLUX (J) DOUBLE UPFIRED (K) RADIANT WALL

Figure 13. BASIC TYPES OF PIPESTILL HEATERS

the catalyst is separated from the products by cyclone separators. The catalyst, fouled by coke and tar during cracking, must be regenerated. This is done in a separate space by passing air through the bed and burning off these products. Figure 14 is a schematic diagram of one type of catalytic cracking unit in operation. The reaction temperatures used in such a unit range from 885° to 950°F, depending upon the yield of products desired. Regenerator temperatures are moderate, ranging from about 1050° to 1200°F. Although operating pressures in this unit are low, 8 to 20 psi, some cracking processes utilize pressures as high as 1000 psi. During catalyst regeneration, when coke and tar are burned off from the catalyst, the combustion gases (primarily carbon monoxide) are sent to carbon monoxide boilers and burned to produce high-pressure steam. The moving-bed cracking process is similar, employing a flowing bead-type catalyst instead of a fine-grain catalyst. Both processes are continuous.

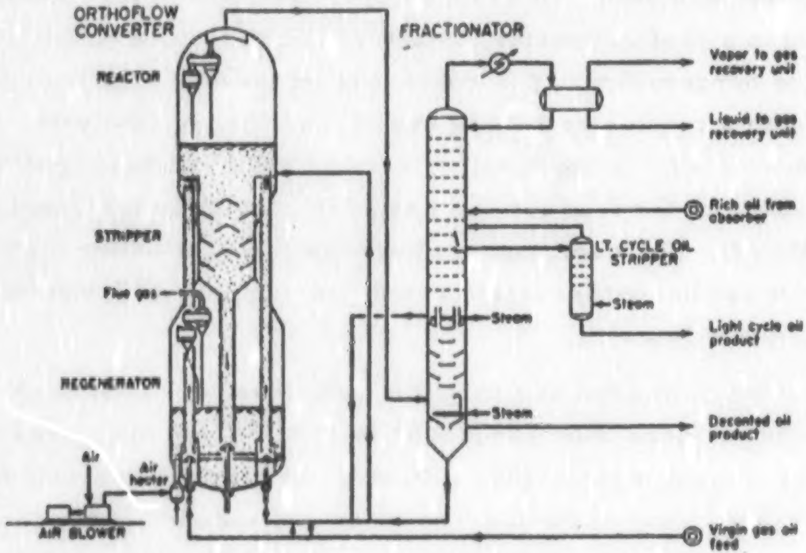
ORTHOFLOW CONVERTER
REACTOR
STRIPPER
Flue gas
REGENERATOR
Air
Air heater
AIR BLOWER
FRACTIONATOR
Vapor to gas recovery unit
Liquid to gas recovery unit
Rich oil from absorber
LT. CYCLE OIL STRIPPER
Steam
Steam
Light cycle oil product
Steam
Decanted oil product
Virgin gas oil feed

Figure 14. SCHEMATIC DIAGRAM OF ORTHOFLOW CATALYTIC CONVERTER AND ADJUNCTS (Stippled Areas Represent Fresh or Regenerated Catalyst) (M. W. Kellogg Co.)

Energy consumption in a typical catalytic cracking process is about 150,000 Btu of fuel and electricity per barrel of feed.* On the other hand, there is a net steam production of about 75 pounds, which converts to a fuel value of 100,000 Btu/bbl of fresh feed.

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* Estimated average based on energy consumed by various processes.

Catalytic Reforming

Catalytic reforming is also an important conversion process within a refinery. In this process, certain ring hydrocarbons are converted into aromatic compounds. As in the case of catalytic cracking, several types of processes are used. In a typical operation, the feed, usually naphtha, is prepared in a prefractionator, mixed with hydrogen, and fed into a preheater, where the temperature of the mixture is increased. The hot naphtha vapors are fed into a reactor containing any of a number of catalysts, depending on the process used. In the reactor, several chemical reactions take place. The products of the reaction are cooled in heat exchangers and then fractionated or stabilized. The stabilized product then can be used for high-octane gasoline, or it can be further fractionated into components (principally benzene, toluene, and xylenes).

Operating conditions of a catalytic reformer vary considerably. Reactor temperatures range from about 800° to 1100°F, and pressures range from as low as 100 psi to more than 1000 psi. Energy consumption also varies considerably. Fuel in the form of oil or gas and electricity are the primary types of energy consumed in catalytic reforming. Fuel consumption varies from 200,000 to 450,000 Btu/bbl of feed. Electric consumption, primarily for driving pumps and compressors, varies from 3000 to 20,000 Btu/bbl of feed.

Delayed Coker

Coking processes are relatively severe cracking operations designed to completely convert residual products such as pitch and tar into gas, naphtha, heating oil, gas oil and coke. Delayed coking is a high energy-consuming process employing fired heaters to heat the charge oil. It is a semicontinuous process in which the heated charge is transferred to large coking drums that provide the long residence time needed to allow the cracking reactions to proceed to completion. A flow plan for a delayed coking process is shown in Figure 15. Feed is introduced into the product fractionator, where it is heated. The fractionator bottoms are routed through a furnace whose outlet temperature varies from 480° to 515°C. The heated

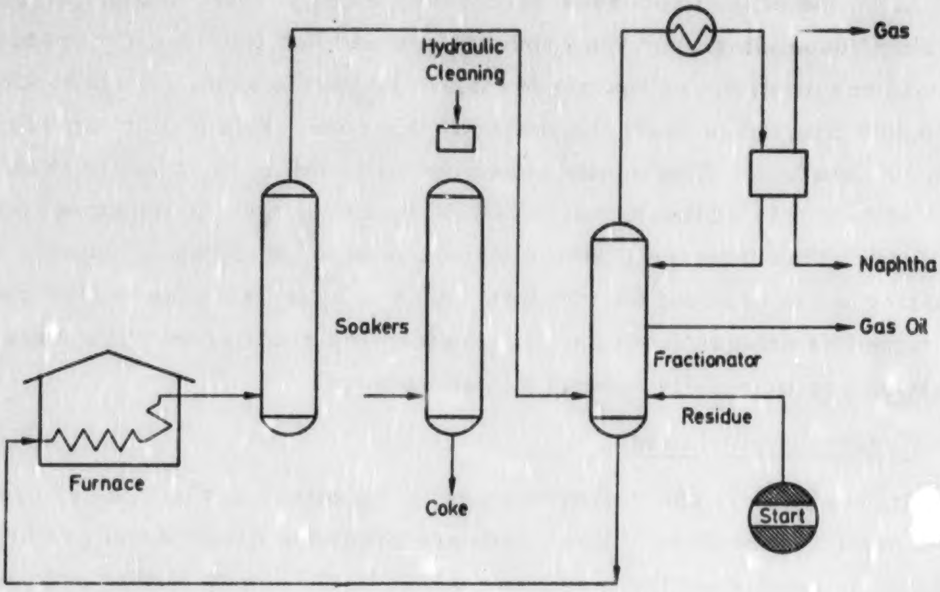

Figure 15. DELAYED COKING PROCESS

oil enters one of a pair of coking drums, where the cracking reactions continue. The products leave at the top, and coke is formed on the inner surface of the drum. The temperature in the coke drums ranges from 415° to 450°C. Overhead products go to the fractionator, where naphtha and heating oil fractions are taken off as products.

Hydrotreating

Hydrotreating is used in a refinery for removing impurities, including sulfur, nitrogen, and metallic compounds; for hydrogen saturation of olefins and aromatics; and for mild hydrocracking. Hydrotreating is used to prepare catalytic cracker and reformer feedstocks and to upgrade middle distillates, cracked fractions, lubricant oils, gasolines, and waxes.

In a typical hydrotreating process, feedstock, made up primarily of petroleum distillates, is mixed with recycle and makeup hydrogen and heated to temperatures of 400° to 850°F. The heated charge then is fed into a fixed-bed reactor containing a catalyst, usually cobalt molybdate on an alumina carrier, and pressurized from 50 to 1500 psig. The effluent is cooled, separated from recycle gas, and stripped of hydrogen sulfide.

As in the other processes discussed, energy consumption varies considerably, depending upon the products desired and the specific process used. Fuel consumption, primarily for heating, varies from 25,000 to about 120,000 Btu/bbl of feed; the majority of processes consume approximately 50,000 Btu/bbl. Electricity consumption is minimal, usually about 7000 Btu/bbl of feed. In addition, about 200 SCF of hydrogen is consumed per barrel of feed. This hydrogen, which should be considered as feedstock, has a heating value of about 65,000 Btu. All the hydrogen used in this process is obtained as off-gas from catalytic reforming processes. The fuels used for heating are primarily natural gas and fuel oil.

Energy Requirements

Approximately 250 refineries are in operation in the U.S. at present, no two of which are alike. Each refinery produces hundreds of products by using the processes that are most suited to the needs of that refinery. The list of factors that affect the choice of the process used by a refinery is long, but the primary ones are crude oil source, power source, water availability, and potential markets. As a result, the energy consumed by a refinery to process a barrel of crude oil varies considerably. A reasonable average, determined by taking the total energy consumption of the industry and dividing by the number of barrels of crude oil run to stills, is about 700,000 Btu/bbl of crude oil processed. Figure 16 compares the various forms of energy consumed by refineries and shows that about two-thirds of the total energy consumption is in the form of natural gas and refinery gas. Purchased electricity, not shown in Figure 16, accounts for less than 3% of the total energy consumption. Other forms of energy, which make up the balance of energy consumed but are not shown in Figure 16, are acid sludge, petroleum coke, liquified petroleum gas, and purchased steam. Together, these forms of energy account for about 16% of the total energy consumed by this industry.

Emissions

Data on the emission of air pollutants from fired heaters (or for that matter any process in the petroleum refining industry) are not readily available. None of the companies interviewed were eager to discuss this subject and the small amount of data available is extremely superficial in nature. What follows is, therefore, merely a general discussion of the emissions from

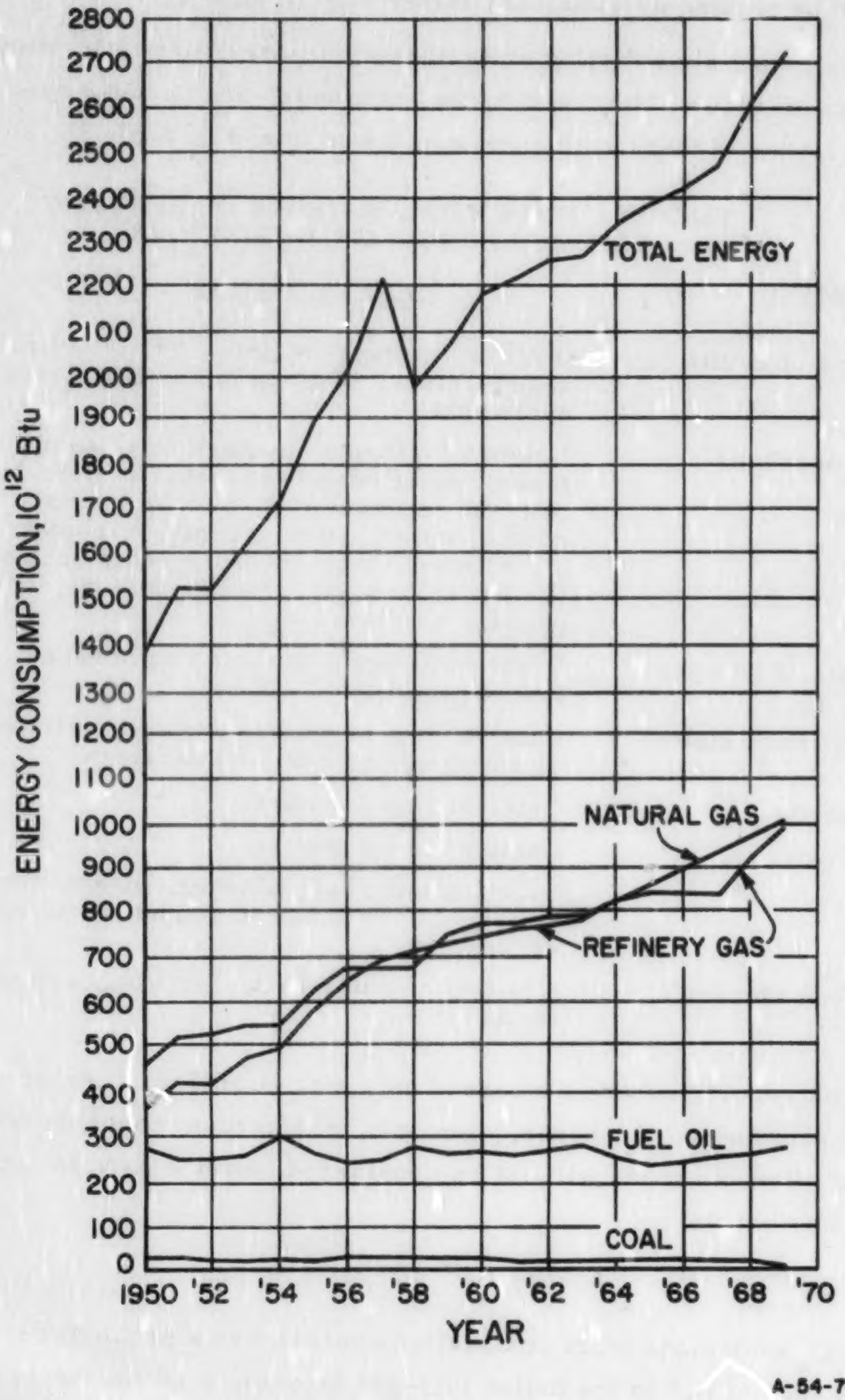

Figure 16. TYPES OF FUEL CONSUMED BY PETROLEUM REFINERIES

combustion sources in the refining process. Any specific data presented should be treated as estimates rather than hard fact.

The major air pollutant emissions from petroleum refineries are SO_x, carbon monoxide, NO_x, aldehydes, ammonia, and particulates. The potential sources of these emissions are summarized in Table 15.

Table 15. POTENTIAL SOURCES OF SPECIFIC EMISSIONS FROM OIL REFINERIES

Emission	Potential Sources
Oxides of Sulfur	Boilers, process heaters, catalytic cracking unit regenerators, treating units, H_2S flares, decoking operations.
Hydrocarbons	Loading facilities, turnarounds, sampling, storage tanks, waste water separators, blow-down systems, catalyst regenerators, pumps, valves, blind changing, cooling towers, vacuum jets, barometric condensers, air-blowing, high pressure equipment handling volatile hydrocarbons, process heaters, boilers, compressor engines.
Oxides of Nitrogen	Process heaters, boilers, compressor engines, catalyst regenerators, flares.
Particulate Matter	Catalyst regenerators, boilers, process heaters, decoking operations, incinerators.
Aldehydes	Catalyst regenerators.
Ammonia	Catalyst regenerators.
Odors	Treating units (air-blowing, steam-blowing), drains, tank vents, barometric condensor sumps, waste water separators.
Carbon Monoxide	Catalyst regeneration, decoking, compressor engines, incinerators.

In this report, we are concerned only with emissions from combustion sources, thus eliminating aldehydes, ammonia, and carbon monoxide from consideration. Hydrocarbons will not be considered because they do not present a serious problem.

SO_x

SO_x emissions from combustion sources are a problem because of the presence of H_2S in the major fuel-gas streams used for firing the heaters. In most refineries, the H_2S in these fuel-gas streams is removed by means of a Claus unit, which converts the H_2S to free sulfur. Under normal circumstances, 95% of the potential sulfur emissions are eliminated. The remaining 5%, rather than being emitted from numerous fired-heater stacks, is consolidated and emitted in the Claus unit stack gases. Cleaning up the remaining 5% requires an expenditure equal to or exceeding the Claus unit expenditure, adding increased investment and labor costs with practically no return.

NO_x

NO_x emissions are estimated to be the most serious problem of all the combustion-related emissions from fired heaters. These emissions from fired heaters are estimated to be about 0.34 lb/10^6 Btu of fuel burned. At the present time, there are no NO_x standards to govern these emissions. However, there is concern that future standards, which might be imposed, would effectively defeat efforts to improve heater efficiency.

Trends in Process Modifications

In general, the petroleum-refining industry is unable to effect substantial process modifications because of the nature of the industry; that is, any modification of processes in one part of the refinery will usually require process modifications in other parts of the refinery to accomodate the first modification. For example, in most existing refineries, the different process units are operated as separate, but nevertheless dependent, entities having intermediate tankage for charge and products, thus providing for flexibility in both operating and maintenance. To improve fuel efficiency, the trend has been to eliminate the intermediate tankage and run hot feed directly from one unit to another. However, such a modification substantially increases the risk of intermediate bottlenecks or reduced stream factors, limiting a completely integrated refinery to an on-stream factor no greater than the lowest of the stream factors of the individual units.

As a result of this interrelationship between processes, most modifications are restricted to improved operating procedures and maintenance. Most of the refineries efforts are concentrated in this area. Thus, refineries are upgrading their process evaluation techniques — for example, by installing more accurate and sensitive flue analysis equipment. Such equipment, it is felt, will allow the process heaters to be fired more efficiently by reducing the amount of excess air used in combustion. The stated goal is 10% excess air for gas-fired heaters and 20% excess air for oil-fired heaters. These goals have not been reached, according to industry representatives, because of the inadequate design of existing burners and inadequate combustion volume on existing heaters.

Two other techniques that have been given consideration for implementation in existing facilities are the use of preheated feed to the heaters and the use of preheated combustion air. Both of these modifications can be readily implemented on existing facilities without requiring substantial modifications to the overall refinery.

Long-range projects for continued improvements in fuel conservation involving the replacement of obsolete equipment with equipment of improved design are being examined by the industry. A comparison of past practice with future design possibilities shows the potential for improved fuel efficiency:

	Past Practice	Future Designs
Lowest temperature for heat removal by exchange	400°F	250°F
Furnace stack temperature	800°F	400°F

They recognize that furnace tube outside skin temperature will be a consideration for the future designs because surfaces will have to be kept above the dewpoint of the furnace gases.

Conservation coordinators feel that retrofit installations of air heaters and steam coils can be justified at current high fuel prices. In completely new installations they will expect to have a greater ratio of convection surface to radiant service. Increased use of extended surface convection furnace tubes is expected. One group favored a furnace design that will eliminate the damper in the breeching to the stack, using instead an air supply box servicing multiple burners. Such installations would provide dampers on the forced air supply to the windboxes. It is clear that, while short-range process modifications for reducing fuel consumption are extremely limited, long-range projections show substantial potential. However, the actual implementation of long-range modifications is likely to be very slow because it depends on the required replacement of existing equipment which have a relatively long life.

Trends in Energy Utilization

In order to combat the effects of rising fuel costs, the petroleum refining industry, under the auspices of the American Petroleum Institute (API), has instituted a fuel conservation program involving more than 80% of the U. S. refinery capacity. The results of this program were reported as follows:

	Energy Consumption, weighted average for 37 companies, thousand Btu/bbl input
1972 Base Period Total Energy Consumption	667
1972 Base Period Adjustment to 1974	+9
Adjusted 1972 Base Period Total Energy Consumption	676
Less 1974 Last Half Year Total Measured Energy Consumption	624
Energy Conservation Improvement for last half of 1974	52
% Reduction from 1972 Base	7.8%

The position of the industry, as alluded to above, is that only small reductions can be effected in the short term and that only over the long term can large reductions be expected.

According to the industry representatives, fuel availability will have a substantial impact on energy utilization, having a depressing effect on improved efficiency. The use of natural gas, currently amounting to about 31% of the total refinery fuel consumption, is decreasing. It is contended that switching to liquid fuels will require more furnace volume for combustion than is presently available in order to maintain the fuel-utilization efficiency at its current level. Thus, switching to liquid fuels is likely to increase fuel consumption until such a time as new equipment, designed to burn these fuels, is installed. This is obviously a long-term effect. It has been suggested that the impact on fuel-utilization efficiency of switching fuels could be mitigated by the development of better burners. While several companies indicated that they could undertake such a development program, none indicated that they were involved in such a program at the present time.

Trends in Emissions

As the industry sees it, the primary emission problems from combustion sources are SO_x and NO_x. The contention is that neither of these emissions can be controlled to meet standards without severely affecting energy-utilization efficiency. For example, the installation and operation of Claus tail-gas cleanup units for SO_x unquestionably results in high energy consumption, but with no compensating improvement in overall efficiency. Thus, with respect to near-term process modifications, SO_x and NO_x emissions, according to the industry, would increase.

On the other hand, given long-range process modifications involving the redesign and replacement of existing equipment, the potential for reducing energy consumption without increasing emissions is high. This is particularly true in light of the anticipated change in fuel utilization pattern, that is, from gaseous to liquid and solid fuels where under present conditions emissions would be expected to increase. As in other industries, the addition of control equipment to prevent the emissions from increasing would result in additional energy expenditures.

Analysis

Although the typical petroleum refinery is a highly complex series of processes, analysis of the relationship between energy consumption and air pollutant emissions from fired heaters is relatively simple, because the potential factors for affecting this relationship are relatively few in number. Process modifications in the short term that affect energy-utilization efficiency are limited to two areas: improved control of the combustion process; and preheating the inputs, the charge material, and the combustion air, into the relevant processes. Long-term modifications primarily involve the replacement of existing equipment with new equipment designed to accommodate a greater variety of fuels and improve heat transfer to the process loads.

Sufficient information on current emission levels is not available to permit a definitive statement about the effect of the various process modifications on air pollutant emissions, but reason would dictate that improved energy utilization need not result in increased emissions. And it should be noted that, as in the other industries discussed, the addition of emission control equipment will increase the energy consumption of a plant by the amount of energy required to operate the equipment.

Clearly, the control of SO_x is a case in point. None of the process modifications discussed will decrease SO_x emissions, thus requiring that control devices be used at an additional expenditure of energy. On the other hand, switching to fuels other than gas, while not necessarily decreasing the efficiency of energy utilization, could result in increased SO_x emissions, requiring additional control devices and increased energy consumption for the overall process.

On the other hand, NO_x emissions have the potential of being significantly affected by the contemplated process modifications. For example, increases in combustion air preheat temperatures typically result in increased NO_x emissions. But there is enough data available from other industries to indicate that this need not be the case. NO_x emissions will not increase if heat transfer within the particular process is increased, precluding an increase in peak flame temperature, the primary cause of increased NO_x emissions under these circumstances.

Recommendations

The primary problem areas within the petroleum refining industry center on two topics: NO_x emissions and improving dual-fuel capabilities to minimize loss of energy utilization efficiency. With respect to NO_x emissions, it is recommended that a program be undertaken to establish the current status of the industry through actual measurement. This will aid in the development of standards for the industry and in determining whether or not the standards are reasonable in light of future process modifications.

Having established this information, it is recommended that demonstration programs be conducted to establish operating procedures for process modifications, where the amount of energy consumed is reduced without increasing NO_x emissions.

Finally, it is recommended that a program for development of improved dual-fuel burners be undertaken, where it can be shown that the current technology is deficient in allowing a company to switch fuels without affecting efficiency.

APPENDIX A. Weighting System

Weighting Factors

The next step in the selection process is the assigning of weighting factors to each of the restraints in terms of their relative importance. In developing the weighting factors, the following assumptions have been made:

1. All air pollutants are equal in importance.
2. Conservation of energy and reduction of emissions are equal in importance.
3. Industries with no potential for energy conservation or reduction of emissions will be excluded from consideration.

Given these assumptions, the weighting factors are assigned based on a scale of 1 to 10, where 1 is a low-priority and 10 is a high-priority rating. To determine the suitability of a particular industry, the following set of numerical operations would be performed:

1. Base energy consumption x emission index number = emission weighted base number.
2. Estimated potential for energy conservation x emission weighted base number.
3. Estimated potential for reducing emissions x emission weighted base number.
4. Items 2 + 3 = conservation and emission weighted number.

Based on the value obtained in 4 above, the industries for study have been selected with the highest value given the highest priority.

Table A-1 defines the weighting system we used to arrive at the numbers used in the above set of equations.

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Table A-1. WEIGHTING SYSTEM FACTORS

1. Base energy number

The base energy number is arrived at by summing the weighting factors for restraints Nos. 1, 2, and 3, where the following values are assigned (scale 1 → 10):

Restraint No. 1. Energy use in process heat
1 = Low usage; 10 = High usage

Restraint No. 2. Combustion-related uses
1 = No combustion-related uses; 10 = All combustion-related uses

Restraint No. 3. Number of processes
1 = Numerous processes; 10 = One process only

2. Emission index number

The emission index number is arrived at by summing the weighting factors for restraints Nos. 4 and 5. However, since the primary emissions of concern, as indicated in restraint No. 5, are generally directly combustion-related, the emission index number can be based on restraint No. 4 alone with values assigned as follows:

1 = Mostly independent emissions; 10 = mostly combustion-related emissions

3. Potential for energy conservation

1 = Low potential; 10 = High potential

4. Potential for reducing emissions

1 = Low potential; 10 = High potential